TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

MIKKO ERONEN

CUSTOMER VALUE AND PROFITABILITY OF POWER TRANSFORMER ONLINE DGA MONITORING

Master of Science Thesis

Examiner: Professor Pekka Verho

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ABSTRACT

MIKKO ERONEN: Customer Value and Profitability of Power Transformer Online DGA Monitoring
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This Master thesis defines the profitability for power transformer online *dissolved gas analysis* (DGA) monitor. The thesis studies the condition monitoring practices, decision making processes and the customer value of the online DGA monitor with different customers. It covers four different customer types: power plants, transmission system operators, distribution system operators and industrial factories.

The research problems were studied by getting statistical information about power transformer failures, their effects and caused costs by interviews and literature. To define the customer value of the online DGA monitor, the efficiency to recognize evolving failures was compared to already existing methods. The actual investment profitability was evaluated by calculating the internal rate of return and payback period. For these methods, the cash flow analysis from the costs and benefits of the DGA monitor was made.

The results were, that the online DGA monitor recognizes the evolving failures with the efficiency of 90 % while the number without it is 50 %. The internal rate of return was positive with all the customer types. However, for distribution system operators it was less than 10 % which can be interpreted as questionable while with other customer types the corresponding number was more than 10 % which can be evaluated as profitable. Also the payback period of distribution system operators is questionable with 4-10 years while with the other customer types it was profitable with the corresponding number less than 4 years.

As a conclusion, it was stated that the direct savings from automated condition monitoring are not enough to justify the online DGA monitoring investment. Instead, the customer value of the indirect cost savings is the greatest with power plants and industrial factories while with the transmission and distribution system operators the corresponding numbers are weak. The poor profitability with indirect cost savings with transmission system operators is due to the N-1 criterion which, in practice, prevents the transmission outages. In these situations, the greatest value for online monitoring is that most of the expensive failures can be recognized and converted into minor maintenance activities. The relatively low price and the good availability of the distribution power transformers are the reason why online DGA monitoring is not profitable for them.

The role of the insurance companies is not significant, what it comes to online DGA monitoring. The deductibles are higher than the price of the online DGA unit, so the monitoring can be seen as profitable despite the insurances.

TIIVISTELMÄ

MIKKO ERONEN: Asiakasarvo ja kannattavuus tehomuuntajien reaaliaikaiselle vikakaasumonitoroinnille
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Tässä diplomityössä määritetään kannattavuutta tehomuuntajien reaaliaikaiselle vikakaasumonitorille. Työ perehtyy eri asiakkaiden kunnonvalvontamenetelmiin ja investointien päätöksentekoprosesseihin, sekä tutkii tämän DGA-monitorin asiakasarvoa. Työ käsittelee asiaa neljän eri asiakastyypin näkökulmasta, jotka ovat voimalaitokset, siirtoverkkoyhtiöt, jakeluverkkoyhtiöt sekä teollisuuden tuotantolaitokset.

Tutkimusongelmiin perehdyttiin hankkimalla tilastotietoa tehomuuntajien vikaantumisista, vaikutuksista sekä aiheutuneista kustannuksista haastattelujen ja kirjallisuuden avulla. DGA-monitorin asiakasarvon määritystä varten selvitettiin, kuinka paljon tehokkaammin monitori tunnistaa kehittyvät viat nykyisiin, jo käytössä oleviin menetelmiin verrattuna. Varsinaista investoinnin kannattavuutta arvioitiin sisäisen korkokannan sekä takaisinmaksuajan määrityksen menetelmillä, joita varten muodostettiin kassavirtalaskelma monitoroinnista aiheutuvista vuotuisista kustannuksista ja säästöistä.

Tuloksiksi saatiin, että DGA-monitori tunnistaa kehittyvät viat lähes 90 % tarkkuudella, kun vanhoilla menetelmillä vastaava luku on 50 %. Investointien sisäinen korkokanta asettui kaikilla asiakasryhmille positiiviseksi kuitenkin siten, että jakeluverkkoyhtiöillä kannattavuus jäi kyseenalaiselle tasolle ollen alle 10 % kun muiden asiakasryhmien kohdalla vastaava luku oli kannattava eli yli 10 %. Myös investoinnin takaisinmaksuaika oli jakeluverkkoyhtiöillä kyseenalainen, eli 4-10 vuotta, kun muiden kohdalla vastaava luku oli kannattava ollen alle 4 vuotta.

Johtopäätöksinä todettiin, että DGA-monitorin tuomat suorat säästöt automatisoidun kunnonvalvonnan seurauksena eivät yksin riitä perusteeksi sen hankinnalle. Asiakasarvo on voimalaitos- ja teollisuusasiakkailla suurimmillaan välillisissä säästöissä, kun taas siirto- ja jakeluverkkoyhtiöiden kohdalla vastaavat luvut ovat heikkoja. Huono kannattavuus välillisten kustannusten osalta johtuu siirtoverkkoyhtiöllä N-1 kriteeristä, joka käytännössä estää siirtokatkokset. Näissä tapauksissa suurin arvo monitoroinnille on, että suuri osa kalliista muuntajavikaantumisista saadaan ennakoitua ja siten muutettua pienemmiksi korjauskuluiksi. Jakeluverkkomuuntajien suhteellisen edullinen hinta ja nopea saatavuus aiheuttaa sen, että DGA-monitorin hankinta ei ole heille järkevää.

Vakuutusyhtiöiden rooli DGA-monitorin hankinnassa ei ole merkittävä. Vakuutusten omavastuut ovat huomattavasti suurempia kuin DGA-monitorin hinta, jolloin monitorointi voidaan nähdä kannattavana vakuutuksista huolimatta.

PREFACE

This thesis was written for Vaisala Oyj. I am thankful to Vaisala as a company for providing me this interesting topic.

I want to thank my instructor M.Sc. Senja Leivo from Vaisala for this opportunity, and my examiner Professor Pekka Verho for feedback, guidance and constructive comments during the work. Also I want to thank all the colleagues from Vaisala and companies and organizations who I was able to have interviews and discussions with.

I want to thank all my friends for making my studies and life so awesome for the past 7 years. Especially Rankat Ankat, Sähkökilta and the Student Union have offered me not only extracurricular activities, but also a great number of new friends and memorable experiences. I also want to thank my family for the support they gave me during my studies.

Lastly, thank you Kia for the ever-patient encouragement and support.

Tampere, 26.10.2016

Mikko Eronen

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LIST OF SYMBOLS AND ABBREVIATIONS

C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6	Ethane
CBM	Condition-Based Maintenance
CEN	Controlled Environment
CH_4	Methane
CIGRE	International Council on Large Electric Systems
CIRED	International Conference on Electricity Distribution
CO	Carbon monoxide
CO_2	Carbon dioxide
D1	Discharges of low energy
D2	Discharges of high energy
DGA	Dissolved Gas Analysis
DSO	Distribution System Operator
DT	Mix of thermal and electrical faults
ed.	Edition
GSU	Generation Step-Up
H_2	Hydrogen
H_20	Water (moisture)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IRR	Internal rate of return
IT	Information technology
NPV	Net present value
OEM	Original Equipment Manufacturer
PD	Partial discharge
T1	Thermal fault, t < 300 °C
T2	Thermal fault, 300 °C < t < 700 °C
T3	Thermal fault, t > 700 °C
TB	Technical Brochure
TBM	Time-Based Maintenance
TCO	Total cost of ownership
TSO	Transmission System Operator
vs.	Versus
WEA	Weather

A_1	*Aging acceleration factor at extra load without monitoring*
A_2	*Aging acceleration factor at extra load with monitoring*
B_F	*Reduced failure-related repair or replacement costs [€/a]*
B_M	*Annual preventive maintenance benefit from online monitoring [€/a]*
B_O	*Total Value of the online DGA monitor in transformer overloading [€/a]*
B_{O1}	*Transformer overloading benefit without online monitoring [€/a]*
B_{O2}	*Transformer overloading benefit with online monitoring [€/a]*
C_A	*Acquisition costs [€]*
C_i	*Total cost of insurances [€]*
C_{ibus}	*Cost of business interruption insurance [€]*
C_{ilia}	*Cost of liability insurance [€]*

C_{ipro}	*Cost of property insurance [€]*
C_{lab}	*Cost of oil analysis in laboratory [€]*
C_{log}	*Logistic costs [€]*
C_{lp}	*Cost of loss of production [€/d]*
$C_{nd(N-0)}$	*Total value of the online DGA monitor in reducing the not delivered energy, N-0 [€/a]*
$C_{nd(N-1)}$	*Total value of the online DGA monitor in reducing the not delivered energy, N-1 [€/a]*
$C_{nd1(N-0)}$	*Cost of contractual power not delivered without online monitoring, N-0*
$C_{nd1(N-1)}$	*Cost of contractual power not delivered without online monitoring, N-1*
$C_{nd2(N-0)}$	*Cost of contractual power not delivered with online monitoring, N-0*
$C_{nd2(N-1)}$	*Cost of contractual power not delivered with online monitoring, N-1*
C_{ng}	*Total value of the online DGA monitor in reducing the not generated power [€/a]*
C_{ng1}	*Cost of power not generated without online monitoring [€/a]*
C_{ng2}	*Cost of power not generated with online monitoring [€/a]*
C_P	*Possession costs [€]*
C_{plan}	*General planning costs [€]*
C_{pre}	*Predictive repair costs for system with early detection [€]*
C_R	*Cost of replacement energy [€/MWh]*
C_{rep}	*Repair costs [€]*
C_{tlp}	*Total value of the online DGA monitor in reducing the lost production in industrial plant [€/a]*
C_{tlp1}	*Total cost for loss of production without online monitoring [€/a]*
C_{tlp2}	*Total cost for loss of production with online monitoring [€/a]*
C_{tr}	*Cost of a new transformer [€]*
C_U	*Usage costs [€]*
C_v	*Cost of each site visit [€]*
D_i	*Total deductible of insurances*
D_{ibus}	*Deductible of business interruption insurance [m]*
D_{ilia}	*Deductible of liability insurance [€]*
D_{ipro}	*Deductible of property insurance [€]*
E	*Expected monitoring system efficiency [%]*
E_1	*Primary voltage [V]*
E_2	*Secondary voltage [V]*
f_{load}	*Power transformer load rate [%]*
I	*Interest rate [%]*
i	*The discount rate [%]*
I_1	*Primary current [A]*
I_2	*Secondary current [A]*
N	*Investment period [a]*
N_1	*Number of primary coil turns*
N_2	*Number of secondary coil turns*
n_i	*Number of failures in i-th year*
N_i	*Number of power transformers operating in i-th year*
N_{voff}	*Number of offline oil samples without online DGA monitoring [1/a]*
N_{von}	*Number of offline oil samples with online DGA monitoring [1/a]*
P	*Nominal power of a power transformer [MVA]*

p_{cat}	*Proportion of failures that are catastrophic [%]*
P_{E1}	*Extra loading without monitoring [%]*
P_{E2}	*Extra loading with monitoring [%]*
p_f	*Power transformer failure rate [%]*
p_{f2}	*Probability of a minor failure on backup transformer [%]*
p_{nd}	*Current rate of not detectable failures [%]*
p_{noncat}	*Proportion of failures that are non-catastrophic [%]*
R_t	*The net cash flow*
t	*Number of the year*
T	*Reference period (normally one year)*
t_{ext}	*Lifetime extension [a]*
T_i	*Reference period of i-th population [a]*
t_{ol}	*Duration of overloading [h/a]*
t_{outage}	*Duration of outage [h]*
$t_{outage2}$	*Duration of a minor failure on backup transformer [h]*
t_{tr}	*Transformer normal life duration [h]*
t_{year}	*Duration of a year in days [d]*
V_D	*Value of delivered energy [€ / MWh]*
V_{nd}	*Value of energy not delivered [€ / MWh]*
V_R	*Transformer replacement referral value because of the online monitoring [€/ a]*
X	*Multiplier for a major failure repair costs*
Y	*Multiplier for catastrophic failure repair costs*
λ	*The annual power transformer failure rate [%]*

€	Euro
°C	Celsius Degree
A	Ampere
a	Year
h	Hour
k	Kilo
M	Mega
m	Month
V	Volt
W	Watt

1. INTRODUCTION

Every year hundreds of power transformers fail. Some of them will fail catastrophically which can lead to dangerous situations, explosions, damage to the people and the nature. Costs may increase to tens of millions of euros. The problem is, that nobody knows which transformers are going to fail and the consequences may be hazardous.

When there is an evolving fault in a power transformer, it forms gases to insulation oil, which can be recognized with the right kind of measurement devices. Today's technology makes it possible to take oil samples from power transformer followed laboratory analysis. This method is called as *dissolved gas analysis* (DGA)

Vaisala Oyj has developed a device which monitors power transformer in almost real-time. Oil samples are taken once in an hour and analyzed immediately. This device is called Vaisala Optimus^{TM} DGA Monitor and it is now available in Vaisala's product offering. Online DGA monitoring saves power transformer owners' money by preventing failures and therefore extending their lifetime.

1.1 Goal for the Thesis

The goal for this thesis is to find the value that a DGA monitor is providing to the customer when he considers to invest in online monitoring. This helps Vaisala personnel to understand the customers' processes and business, and give background information for the pricing and sales argumentation.

The scope of the thesis includes *transmission system operators* (TSO), *distribution system operators* (DSO), generation companies with *generation step-up* (GSU) transformers and industrial customers such as factories. Also the role of insurance companies is covered while discussing about the total cost of a power transformer failure.

The research methods have been mostly the literature review and expert interviews in Vaisala and with potential customers, other stakeholders and industrial experts for DGA monitor. The main literature information have been CIGRE *Technical Brochures* (TB) and IEEE and IEC standards, but also other sources of information exist a lot.

1.2 Thesis Structure

The thesis structure is the following:

- Chapter 1: Introduction
- Chapter 2: Research Environment and Methodology
- Chapter 3: Power Transformer Condition Monitoring as Part of the Asset Management
- Chapter 4: Power Transformer Failure Risk Reduction as the Result of Online DGA Monitoring
- Chapter 5: Factors Affecting Investment Decisions
- Chapter 6: Economic Review
- Chapter 7: Results and Discussion

The Chapter 2 presents the target company Vaisala Oyj, explains the research objectives and methods and gives the motivation for the thesis. Also the previous research about the topic and the scope of this thesis is clarified.

The Chapter 3 explains the operation principle of a power transformer and explains the meaning of asset management. Also different maintenance strategies and condition monitoring practices with different customer types are covered, and the DGA analysis is explained in more detailed level. The Chapter 4 explains the power transformer failure risk and how the online DGA monitoring can decrease it. Also the consequences and external effects of a failure are discussed.

The Chapter 5 discusses about the investment decision making process on different company levels. Also the customer value of the DGA monitor is defined with benefits and sacrifices, and the equations and the monetary terms for the customer value calculations are presented. In the Chapter 6, the equations and calculations for profitability are made and the valid value proposition are evaluated.

In the Chapter 7 the profitability calculation results are analyzed and the whole thesis is discussed. The Chapter includes a conclusion, evaluation of the thesis and recommendations for Vaisala for the future actions.

Appendices include the interview questionnaire which was used while doing the thesis and the cash flow analysis Tables which were created while doing the thesis.

2. RESEARCH ENVIRONMENT AND METHODOLOGY

This Chapter introduces Vaisala Oyj as a company, the project background and the actual research problem and its scope. Also, it presents and explains earlier research on topic and the used research methods.

2.1 Vaisala Oyj as a Company

Vaisala Oyj was founded in 1936 in Finland. Company's core business is environmental measurement specialized to weather measurement and industrial measurement. Its business is divided to two areas: *Weather* (WEA) and *Controlled Environment* (CEN). (Vaisala Web-site 2016) This thesis focuses to CEN.

Vaisala is innovative and customer focused company which offers reliable environmental observations for better decision making, safety and efficiency. The company uses lot of capital to research and development activities and also works closely with research institutes and universities. (Vaisala Web-site 2016)

Nowadays the company serves customers in more than 150 countries. In Vaisala there are more than 900 employees in Finland and almost 1600 globally (numbers December 31, 2015). (Vaisala Web-site 2016)

2.2 Project Background

Vaisala Oyj has been developing a new monitoring device for power transformer online monitoring since 2013. This product, called Vaisala Optimus™ DGA Monitor, was officially launched in early May 2016 and the deliveries to the customers should start in Quarter 4 of 2016. Later in this thesis the device is called as online DGA monitor. The operation method of the online DGA monitor is covered later in the Chapter 3.

The online DGA monitor business is widely competed since the first devices came to the market in 1990's. Now, almost two decades later, Vaisala saw the new business opportunity for itself and is now entering the already existing, but clearly growing market.

It is important to understand end-users and their needs better. The customer value is always a subjective experience and depends on a customer and its current situation in its own industry. Therefore, it is crucial to understand the differences between the customers all over the world in different kinds of circumstances.

2.3 Research Objectives and Questions

The actual research problem is that so far it has not been clear that what are the relevant issues and facts when a customer considers to invest in online DGA monitor. Different customers work in different business environment and in different industries.

The goal of this thesis is to provide information about customer value and help the sales personnel to figure out the additional sales arguments for the device as it aims to understand various potential customers. Also the strategic product management is considered as a target group for this thesis.

The main research objectives formed with Vaisala are:

- to understand power transformer asset management, maintenance strategies and condition monitoring practices,
- to gather information about the power transformer failure rates and understand how the online DGA monitor can decrease it,
- to understand the customers' investment decision making processes,
- to learn about the customer value creation, *total cost of ownership* (TCO) of the online DGA monitor and the total cost of a power transformer failure,
- to make actual investment calculations for online DGA monitor investment and
- to understand the scenarios where online DGA monitor whether is or is not a profitable investment.

Research questions give guidance for the power transformer failures and their costs. These questions were taken into account when the actual interview questions (Appendix A) were formed:

- When company has the X number of power transformers, how often one fails? How often it is a minor, major or catastrophic failure?
- What are the main reasons for a power transformer failure?
- How much more failures the online DGA monitor can prevent compared with the DGA offline sampling?
- What are the main things which are driving the decision making process when thinking about investing in monitoring?
- What are the expenses of ordering and installing a new power transformer? How about the costs of lost production and other indirect costs in case of a failure?
- What is the required return on investment when deciding whether to make an investment or not?

2.4 Research Scope and Limitations

This sub-chapter describes the topic of this thesis in a wider context and clarifies the limitations and the scope. There are power transformers in multiple locations in the electricity system. First, there are GSU transformers in power generating stations, then transmission transformers and distribution transformers. Also, some industrial customers have their own power transformers.

The focus of the thesis is global as the available literature and statistics are also global. However, not companies from every country are included, but since power transformer technology and the industry as a whole are pretty similar all over the world, it is possible to make global estimations and conclusions. Still, it is important to understand that statistics present the industry averages and, therefore, big variation actually exists between the countries, industries, companies and even with the individual power transformers.

The Figure 2.1 presents the scope of the thesis within the power transformer asset management process. The orange color signals the scope. The scope of the Master thesis.

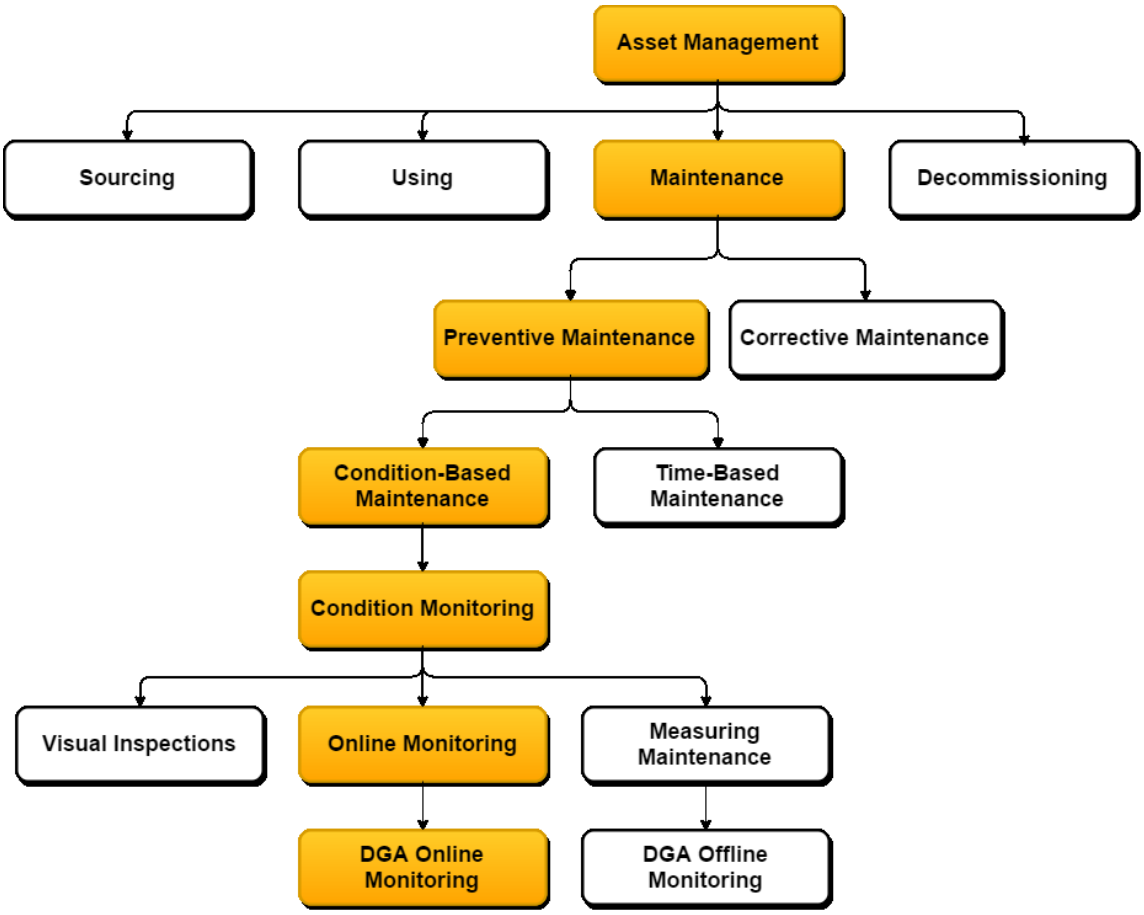

Figure 2.1 The Scope of the Master Thesis.

The Figure 2.1 presents that the asset management is divided into four parts, while this thesis concentrates on maintenance. The maintenance is consisting of two strategies which the preventive maintenance strategy is covered in the thesis. Again, the preventive maintenance can be seen as a sum of *condition-based maintenance* (CBM) and *time-based maintenance* (TBM) while this thesis focuses on CBM. The CBM then can be covered by visual inspections, online monitoring and measuring maintenance. This thesis enters into online monitoring and, more specific, online DGA monitoring.

Out of the scope are:

- other monitoring methods,
- differences between the power transformer types and oil types,
- Vaisala's own processes,
- regulation and
- financial markets.

These exclusions were done because of the several reasons. First, including all the mentioned issues would not be realistic as covering all the possible power transformer types with all the possible oil types in every imaginable circumstances cannot be done in one master thesis project. Second, this thesis is made totally from Vaisala's customers' perspective, so its own processes or profitability is not relevant

2.5 Previous Research on Topic

Research papers that discuss about the customer value or profitability for power transformer online monitors were not readily available. Thus, other resources and expert interviews became crucial. Highly important and useful information about the power transformer failure statistics was available from several publishers. The most advanced resources about the topic are published by IEC, IEEE and CIGRE. Their several standards and technical brochures include a lot of expert insight about the industry.

Second part of the thesis is about accounting and investment calculations. As suspected in advance, that area is widely covered by existing literature. However, the crucial thing was to get the power transformer statistics which were then used as an input while doing the calculations. In this section of the thesis, especially Hutt & Speh (2013), Suomala et al. (2011) and CIGRE TB 642 (2015) included highly important information as well as IEEE C57.143.

2.6 Research Methods

The key thing in choosing the research strategy is that it answers the research problem and meets the objectives (Saunders et al. 2009). The Figure 2.2 presents the strategy choosing procedures for this thesis.

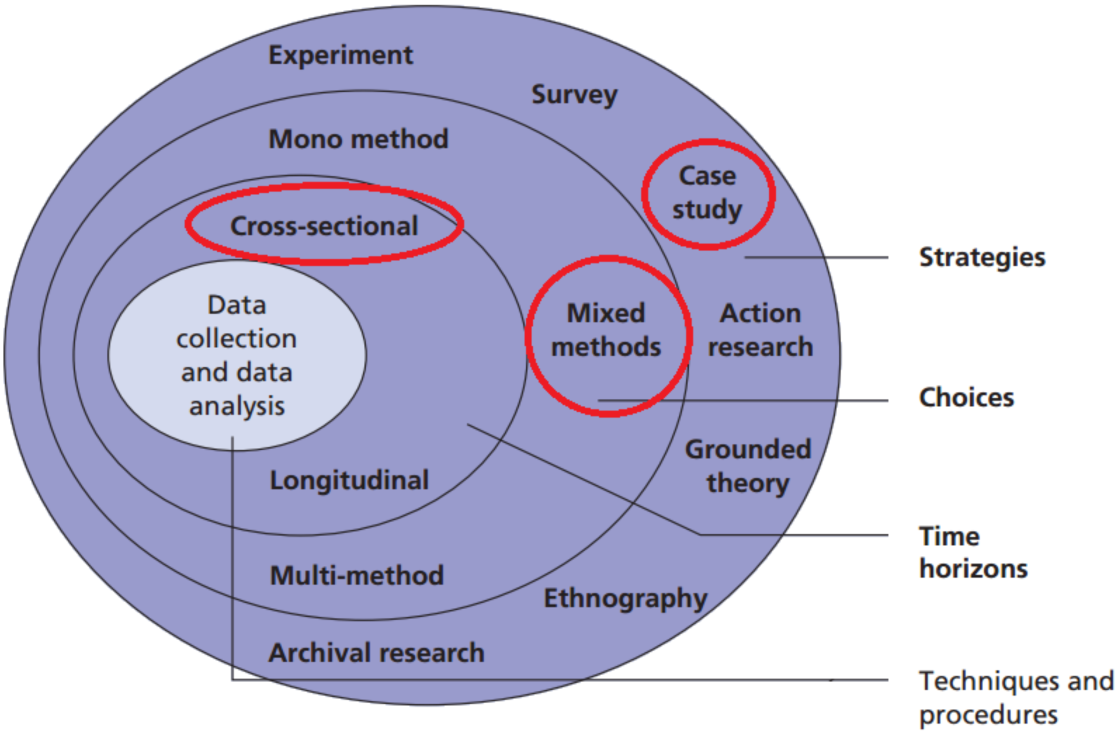

Figure 2.2 The Research 'Onion' (Saunders et al. 2009, modified).

This thesis is considered as a case study. According to Robson (2002), a case study is "a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence". The phenomenon in this thesis is the profitability of the investment in online DGA monitoring.

Mixed methods were used as they combine both quantitative and qualitative methods. Quantitative means data collection and analysis methods that generate or use numerical data, whereas qualitative methods use and analyze non-numerical data (Saunders et al. 2009). Various data collection techniques were used in this thesis, and they include, for example, interviews, statistics and documentary analyzes.

A longitudinal research studies a change or development over time while cross-sectional research studies a particular phenomenon in a particular time (Saunders et al. 2009). This thesis is a cross-sectional study, since the main interest is in the current state rather than in the change.

The center of the research onion is data collection and data analysis. The following subchapters cover these aspects.

2.6.1 Literature Review

Lots of qualitative literature was used in this thesis. The main resources were IEC, IEEE and CIGRE. IEC and IEEE has several international standards about power transformers, asset management and condition monitoring, which were all highly beneficial resources for this thesis. From CIGRE, technical brochures and expert publications were used a lot. Also CIRED and a few doctoral dissertations present the main source of information.

The information about the power transformer failure rates, the practices of different industries, information about the power transformer failure modes and locations, benefits and costs related to the online DGA monitoring and power transformer failures were gathered from industry literature. In accounting and investment calculations part of the thesis, university level educational books were used for customer value and equations.

2.6.2 Personal Interviews

In this thesis several experts are interviewed. Some of them are Vaisala employees but most of them are the industry experts outside Vaisala. All the contacts were first contacted through e-mail, phone, exhibitions or social media services. In this thesis, telephone interviews are categorized as personal interviews.

According to Saunders et al. (2009), a good way to categorize the personal interviews is to divide them into three:

- structured interviews,
- unstructured interviews and
- semi-structured interviews.

Structured interviews are often used when quantitative data is needed. In this method a sample needs to be big so that conclusions can be made. (Saunders et al. 2009) All the interviewees are asked the same questions in the same order. Structured interviews were not used while doing this thesis.

Unstructured interviews were used in small amounts in the thesis. They are informal conversations without actual questionnaire or survey. However, the questions emerge from the conversation and its topic. Unstructured interview is considered to be qualitative research method (Saunders et al. 2009).

Semi-structured interviews are based on a list of topic and questions which can be different for every interviewees. This type of interview was used in almost all the interviews in this thesis, and, according to Saunders et al. (2009), it is also considered to be qualitative research method. In this method, the interviewer decides the asked questions and their order. In general, the given answers lead to the new questions which the interviewer presents immediately.

The theme of the interview and the topic of the thesis was sent to the interviewees beforehand so they could prepare for the interview. The questions are listed in the Appendix A. The first questions about the company, experience and the relation with the power transformers were always asked in a same sequence. Some questions, which were not in the expert field of an interviewee, were usually left out. For example, oil laboratory personnel were not asked about the indirect costs of a failed power transformer.

All the personal interviews are listed in references in the end of the thesis.

2.6.3 E-mail Interviews

Some interviews were executed via e-mail because the actual meeting or phone call was not possible to arrange. All of these interviews were with experts outside Vaisala. The interviewees were first contacted through e-mail, exhibitions or social media services.

All the interviews were executed with same questions than the personal interviews. The question document (Appendix A) was sent to the interviewees and they answered the questions freely. Also comments outside the actual questions were given about the topic. In some interviews, the answers led to new questions, which were also asked via new e-mail.

All the e-mail interviews are listed in references in the end of the thesis.

3. POWER TRANSFORMER CONDITION MONITORING AS PART OF THE ASSET MANAGEMENT

As Aro et al. (2011) claims, the availability of the electricity, its supply certainty, safety, production, transmission, distribution, use and the preservation of the environment are setting requirements for electrical equipments' management and maintenance. These things are setting the maintenance into important position.

As a definition, a fault or failure has occurred when the power transformer cannot perform its purpose. After failure the item has a fault. 'Failure' is an event, as distinguished from 'fault', which is a state. (CIGRE TB 227 2003) Outage is the situation where the power transformer is completely disconnected from the system (Elovaara & Haarla 2011a).

3.1 Power Transformer Operation Principle and Structure

Power transformer is an inseparable and one of the most significant part of a power system (Jongen et al. 2007). It is an electrical device which works with the electromagnetic induction and is used to convert the voltage and current from one magnitude to another without changing the frequency (Osbert 2015a; Elovaara & Haarla 2011b). Power transformers are used in power generation to step up the voltage in order to minimize the power losses (Osbert 2014) and, in transmission, distribution and industry, to lower the voltage to actually required level (Osbert 2015a). The basic idea is presented in the Figure 3.1.

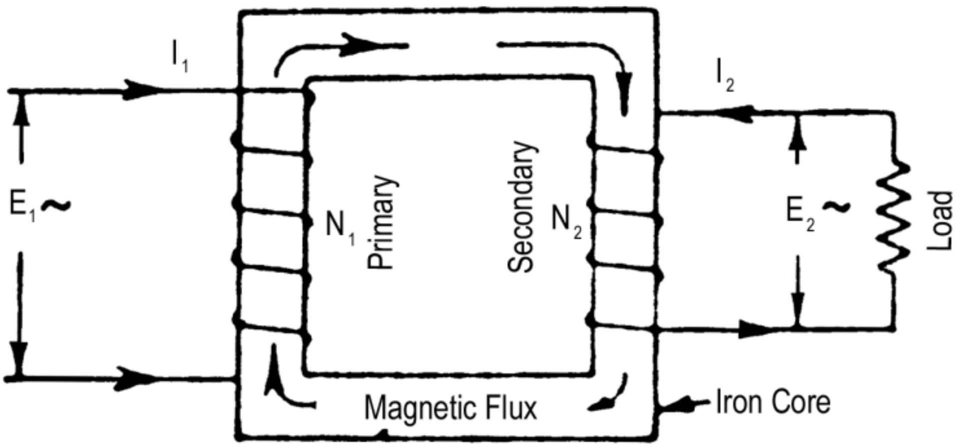

Figure 3.1 Transformer Working Principle (Johnson 2002, modified).

The Figure 3.1 presents the relationship which is established as the ratio of the primary and secondary voltage is equal to the ratio of the primary and secondary windings (Johnson 2002). Windings consist of several turns of copper coils bundled together and all bundles are connected in series to form a winding. There are primary windings for input and secondary windings for output. Transformer consists of two or more windings which are linked together by a mutual magnetic field. The power transformer voltage is directly proportional to the relation of the turns, while the current is inversely proportional. (Johnson 2002) This simplified idea is presented in the equation 1.

$$\frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{I_2}{I_1}, \tag{1}$$

N_1	*Number of primary coil turns,*
N_2	*Number of secondary coil turns,*
E_1	*Primary voltage,*
E_2	*Secondary voltage,*
I_1	*Primary current,*
I_2	*Secondary current*. (Johnson 2002)

The main parts of a power transformer are a laminated core, windings, insulating materials, transformer oil and tap changer (Osbert 2015b). Insulating materials are usually papers and pressboards which are used to isolate primary and secondary windings from each other and from the core. Also the transformer oil, which, in practice, all power transformers are filled with, is insulation material as well as the cooling material (Elovaara & Haarla 2011b). The core and the windings must be completely immersed in the oil (Osbert 2015b).

Osbert (2015b) also states that the output voltage may vary according to the input voltage and the load. During loaded conditions, the voltage on the output terminal decreases and during off load conditions the output voltage increases. In order to balance the voltage variations, the tap changers are used.

3.2 Lifetime of Power Transformer

Power transformers are generally very reliable equipments with expected lifetime of 40 years or more (CIGRE TB 227 2003) while the deviation can be as large as +/- 15 years. A consequence of this is that transformers have to be considered and evaluated as individuals (Pettersson et al. 1998). The technical lifetime of a power transformer is based on the technical condition while the economic lifetime is based on annual operating costs. When the operating costs are higher than the annual investing and operating costs of the new unit, the economic lifetime is expired. In some cases, it is possible that with relocating the transformer, there is still economic lifetime left. (Pylvänäinen 2010)

An important thing to notice is that failures are not due to general number of years in service alone, but can be a consequence of several things (Cross et al. 2014). According to Aro et al. (2011), the actual lifetime depends not only on the device itself, but also its

- structure,
- used materials and their strength,
- measurements,
- manufacturing and testing methods
- aging and
- loading rate.

In addition that power transformer has sufficient electrical and mechanical features, it has to sustain the stress caused by the usage and external factors, such as weather conditions, without getting its properties damaged (CIGRE TB 422 2010). As the IEEE C57.143 states, the problems in power transformers usually arise from manufacturing defects, deterioration processes and operating conditions.

All of these conditions and electrical stress cannot be foreseen in advance and the behavior of the materials in all conditions are not known. Because of the fact that the changes in the power transformer's features during its lifetime cannot be known, the maintenance and condition monitoring is needed. (Aro et al. 2011) These methods are covered later in this thesis.

When reviewing the fault-statistics of power transformers, they are usually presented with a so-called 'bathtub-curve' (CIGRE TB 541 2013). The curve is presented in the Figure 3.2.

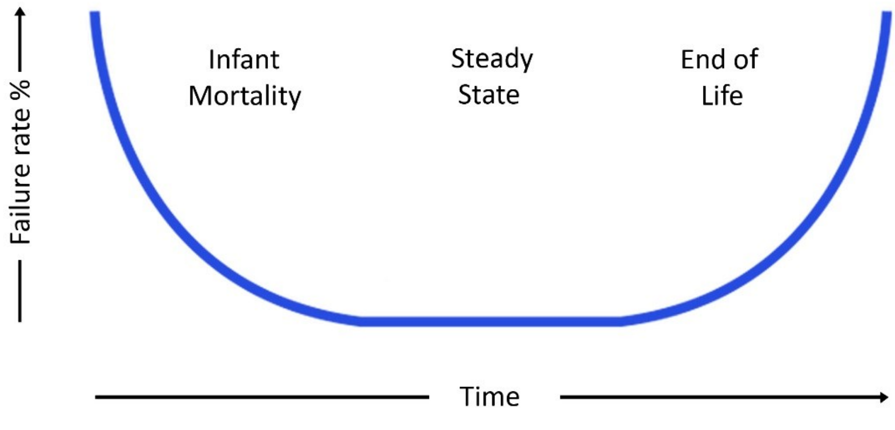

Figure 3.2 The 'Bathtub-Curve' (Veracity Asset Management Group 2016, modified).

As seen from the Figure 3.2, the failure rate varies during a lifetime of a power transformer. According to CIGRE TB 541 (2013), it is possible to recognize three different time intervals: First, in 'infant mortality' phase, which is the consequence of the failures during the assembling period, the failure rate is high. After this, the failure rate remains in a quite low level in a 'steady state' phase. When the lifetime is coming to its end, the failure rate starts to increase again. In practice, this means that the power transformer needs to be replaced.

3.3 Asset Management

IEC (2015) defines an asset as a major item of electrical network equipment, such as a power transformer. Asset management attempts to optimally manage assets and their associated performance, risks and costs. It involves decision making in the network business to minimize the long-term total expenses (Lakervi & Partanen 2008) and, at the same time, to maximize the long term profits (CIGRE TB 422 2010).

Usually asset management is considered to be an issue only for TSOs and DSOs, but generation plants and big industrial users are also power transformer owners. Therefore, it is essential that also they take care of them and do asset management. According to Lakervi & Partanen (2008) the financial requirements are setting the boundaries to resources and investments. As a whole, the asset management is big and complex optimization process which goal is to maintain a safe and high-quality power network which is as profitable as possible (CIGRE TB 248 2004). To simplify this, it is often said that the ultimate objective for asset management is simply “to get the most out of an asset” (CIGRE TB 227 2003).

The challenges of aging equipment and a relatively slow replacement rate are not only technical – they also have very significant financial implications. As IEC (2015) states, it is intuitively deducible that improper asset management will eventually result in additional outages, and that such outages have significant cost. (IEC 2015) Because the power transformer is always a technical-financial investment, compromises are often made if they give financial savings.

According to CIGRE TB 227 (2003), the biggest drivers for asset management nowadays are

- power transformers are getting older and they are approaching/exceeding the end of their expected lifetime,
- fewer people are capable to manage the transformer population,
- pressure to save money by reducing maintenance,
- organizational changes where non-technical personnel are accountable for power transformers and
- new monitoring techniques are becoming available.

The goals for asset management is presented in the Figure 3.3.

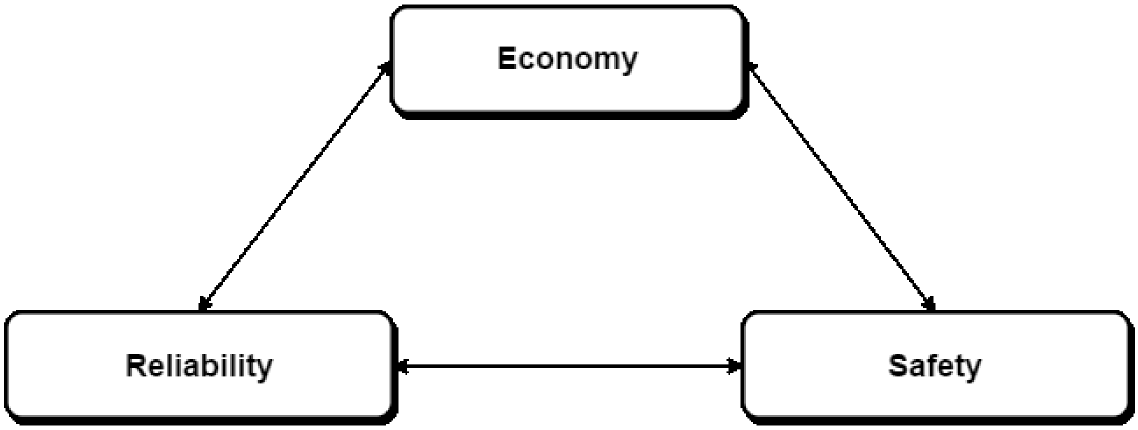

Figure 3.3 Asset Management Goals (Lakervi & Partanen 2008, replicated).

The goals of asset management can be seen as a sum of reliability, safety and economy. All of them has an impact to each other and it is crucial to make sure that all parts are taken care of.

3.4 Maintenance Strategies

To avoid failures and problems, it is essential to conduct a program of careful supervision and maintenance (IEEE C57.93). Maintenance is planned and organized action and operational readiness, which is meant to keep the installed assets in operation. One goal for the maintenance planning is to build as high reliability as possible with as low cost as possible (Verho 2016).

The CIGRE TB 248 (2004) states that the maintenance of a transformer has a high contribution to the lifetime of the unit, as well as to its reliability and availability. *Original equipment manufacturer*s (OEMs) specify the minimum requirements for the maintenance in their instruction manuals. However, power transformer users should have maintenance policies that depend on many factors such as importance of the unit, costs of outages and costs of maintenance.

Therefore, the general goals for maintenance can be listed as

- extending the lifetime of a power transformer,
- securing the optimal usage in all conditions and
- maximizing the return on investments made to power transformers.

There is no one single way to maintain all the power transformers. Most units require individual analysis to find out the best and the most cost-effective plan. The selected plan should balance the best combination of sensitivity, speed and selectivity against the overall economic. (IEEE C37.91)

The maintenance is done because it is cheaper to maintain the power transformer than wait for the actual fault. Failures can cause downtime for a power transformer, which can lead to the high expenses. Also, it is crucial that as much maintenance as possible is done at the same time, so there is no need to visit the power transformer site more often than actually required.

There are two different maintenance strategies (Lakervi & Partanen 2008) which are suitable for different situations. The idea is to minimize the long-term expenses such as investments, interruptions and maintenance costs. These strategies are presented in the Figure 3.4.

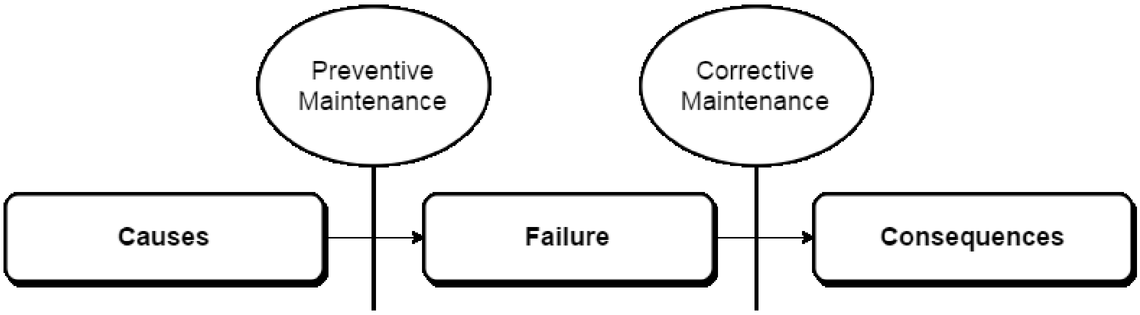

Figure 3.4 Maintenance Strategies.

The strategies are usually divided into preventive and corrective maintenance (Lakervi & Partanen 2008). Preventive maintenance is done in advance to prevent to failure from happening, while corrective maintenance is done after a failure has happened. The strategies are covered more deeply in the following sub-chapters.

While choosing the strategy, the important question is whether it is needed to stop failures from happening or is it enough to fix the failures afterwards. However, all the situations and faults can never been recognized before, because some of them will happen for sudden reasons, such as storm, snow or animals. So, some part of the maintenance will always be corrective maintenance, while good planning and preparation is trying to keep it at the minimum level. (Lakervi & Partanen 2008)

3.4.1 Corrective Maintenance

The corrective maintenance is the most simple maintenance strategy (IEC 2015). With this strategy, the maintenance is done after a fault has happened. After a failure, the component condition is assessed to make a decision whether to repair or replace it (IEC 2015). Aro et al. (2011) states that it is valid strategy when the failures are small and they do not cause interruptions or outages to the system.

The goal for this strategy is to return the failed power transformer to action as fast as possible by doing repairing work (Aro et al. 2011). When the reason to a failure is a part which is easy and fast to replace, this is usually the cheapest and most used method.

However, when the repair is more complex, especially the indirect costs can be really high because of the long interruption time (CIGRE TB 422 2010). This subject is covered later in this thesis.

The important issues with this strategy are correctly measured material and personnel resources. Often the asset owners do not do the maintenance work by themselves but, instead, they have outsourced it to a third party company (Lakervi & Partanen 2008).

3.4.2 Preventive Maintenance

Preventive maintenance is work which is planned and scheduled beforehand. It is done in certain time intervals or before the asset has suffered failures. This method requires skills and possibilities to anticipate the functionality of power transformers (Aro et al. 2011) and the maintenance can be done by both visually and diagnostically (Nousiainen 2015).

With important and expensive components, such as power transformer, it is usually smart to choose the preventive maintenance as a strategy because it would not be effective or financially profitable to start repairing the failures and let the power transformer be out of use for a long time. But, also, preventive maintenance can be taken too far where it is not profitable anymore. For example, by doing extensive overhauls to small-size distribution transformer every year (Lakervi & Partanen 2008). Preventive maintenance is divided to smaller and more specific sections. They are called as TBM and CBM (CIGRE TB 248 2004).

Time Based Maintenance

In TBM, certain maintenance activities are done in specific time-intervals, such as, for example, every month or every 2 years (IEEE C57.93; CIGRE TB 422 2010). The guiding factors are usually the OEM's specifications, international standards and established practices within the company. Also, some time-based activities are often based on local legislation.

According to Nousiainen (2015), regular inspections are done to power transformers because of their importance. At least in Finland it is common to have an extensive midlife overhaul done to power transformer in the age of 25 to 30. This can increase its life span for 15 years (Lakervi & Partanen 2008).

However, the ultimate TBM strategy can lead to the situation where fully workable power transformer is replaced with the new one just based on the time. These situations can be really expensive for nothing if they lead to the oversized and unnecessary maintenance activities. Therefore the CBM strategy was created.

Condition Based Maintenance

Another method for maintenance is CBM. Doing the maintenance based on the condition, instead of the time, it controls the resources to the optimal solution and decreases the number of unnecessary activities (Verho 2016).

In this method, a lot of information and monitoring is needed and, also, capabilities to do estimations for the future on how the possible failures will evolve. This method gives the realistic image from power transformers and the maintenance activities can be directed to the assets which are really needing them. The maintenance activity is launched by the estimated condition reaching certain limit levels which then leads to high availability with moderate maintenance costs (IEC 2015). At the same time the number of disturbances will decrease when the assets can be fixed before actual failures happen.

3.5 Condition Monitoring

Condition monitoring is also part of the maintenance (Luopajärvi 2010). It is any repetitive observations or measurements which can help to detect the development of a failure in a power transformer. The goal of condition monitoring is to identify these failures as early stage as possible as it lowers the costs of required maintenance (CIGRE TB 227 2003). Power transformer outages have considerable economic impact on electrical network. Therefore it is important to ensure an accurate assessment of the power transformer condition.

Condition monitoring always aims to detect when the conditions of the asset are changed so that they can lead to the failures or disturbances. Condition monitoring includes the necessary inspections and measurements, but also the analysis and conclusion. The result for this is to help the asset manager to decide if there is maintenance needed to do (Aro et al. 2011).

The most important reliability factors in power transformers are usually mechanical strength and electrical insulation (CIGRE TB 227 2003). However, the direct measurement of these factors is impossible (Aro et al. 2011; Nousiainen 2015). In practice this means that power transformer has to be monitored indirectly where the changed values are related to the actually important factors (Nousiainen 2015). Technically it is possible to measure many kinds of physical magnitudes, but the key is to understand which of them are giving the useful information (Aro et al. 2011).

The condition monitoring is part of the CBM strategy and the used methods usually include

- visual inspections,
- measuring maintenance and
- online monitoring. (Verho 2016)

3.5.1 Visual Inspections

According to IEEE C57.93, the visual inspections are usually made by human instincts outside the power transformers. Asset professional, who is familiar with the power transformers, goes to the site in person, and visually checks if there has been some changes in power transformers, conditions or surroundings. Some of the targets, such as markings, locks, oil leakages and meters, can be checked visually.

3.5.2 Measuring Maintenance

Measuring maintenance is usually done when visual inspection is not possible or accurate enough. With this method, different kinds of measurements are done to the power transformer to understand the conditions of the asset. Measurements can be, for example, electrical or chemical. These measurements can reveal the evolving faults which are not visible yet, but in the future they would cause problems and failures. With measurements it is possible to target the right maintenance activities to the right parts of the power transformer (Verho 2016).

Measuring maintenance is performed manually by a technician within the power transformer site or substation. It is part of the TBM strategy and is always done in certain time intervals and sometimes it causes an interruption and downtime for a power transformer. There are several methods for different kinds of measurements. Possible measuring targets can be, for example

- oil analysis,
- furfural analysis,
- DGA,
- *partial discharge* (PD) measurements and
- tan φ measurement. (Nousiainen 2015)

This thesis focuses only on DGA which is covered in the sub-chapter 3.6.

3.5.3 Online Monitoring

Online monitoring implies aspects where data can be collected and measured while equipment is energized and in service (CIGRE TB 445 2011). The monitoring does not disturb the monitored channels. The basic goals for online monitoring are

- to generate early warnings in case of incipient faults to reduce the risk of unexpected failure,
- to follow up the development of the diagnostic values on suspect or faulty units which cannot be taken out of service immediately,

- to reduce costs for periodic diagnostic testing and assign workers to other tasks and
- to archive measured and computed data in a database for future analyses. (CIGRE TB 445 2011)

Also the following advantages can be achieved with online monitoring:

- it reduces the condition monitoring task interval nearly to zero compared to offline monitoring,
- it can generate an automatic warning if preset limits or trends are exceeded and
- in case of unexpected failure, it performs a “black box” function which records the data before and after the failure and thus enhances the available evidence used for failure analysis. (CIGRE TB 445 2011)

According to IEEE C57.143, power transformer online monitoring equipment can vary depending on the number of monitored parameters. At the most basic level, only temperature can be monitored and, in contrast, sophisticated monitors can monitor several parameters simultaneously. All the alarms and problems are communicated directly to maintenance personnel in early stage. The elements of the online monitoring system are typically monitoring sensor, indication, electronic hardware, hardware connection, communication interface and data processing.

Online monitoring is usually installed to the assets which are both expensive and critical (Nousiainen 2015; CIGRE TB 248 2004). The closer the power transformer is to generation, the more critical it usually is because the impact to the network is bigger (Alfonso 2016). It is the most advanced level of condition monitoring with its real-time measurement activities. Online monitoring is carried out as frequently as possible, so, as soon as one cycle of measurements is completed the next one is started.

At its best, all the power transformers are monitored with real-time with online monitors. The monitors have the limit values and when they are exceeded, the system gives an alarm (CIGRE TB 227 2003) which goes directly to the asset managers. With that information it is easy to decide what kind of maintenance is needed to be done. IEEE C57.143 states that the continuous monitoring permits timely remedial action. Premature action could result in wasted valuable maintenance resources; late action could result in costly consequences such as failure.

Online monitoring does not prevent failures as such, but it can prevent the costly maintenance associated with transformer failures by allowing the user to take corrective action during the operating life. CIGRE TB 248 (2004) states that the factors which the transformer asset manager needs to consider when determining if the online monitoring system is needed or not are:

- equipment reliability and maintenance costs,
- benefit from increased reliability,
- cost of equipment, installation and training,
- future benefit of additional information for transformer condition determination,
- value of information and
- cost of data archiving and retrieval.

As well as the measuring maintenance, the online monitoring can also be done with multiple ways. This thesis focuses only on online DGA monitoring, which is the main monitoring tool for condition monitoring (Duval 2016b). The DGA method is covered in the sub-chapter 3.6.

3.6 DGA Analysis and Diagnostics

DGA is fully diagnostic method for analyzing the condition of power transformers. It combines the measurement, identification and interpretation of gases dissolved in the power transformer insulation oil (IEEE C57.139). It usually is the main, and in some cases, the only method with which it is possible to monitor and diagnose the condition of a power transformers (Grisaru & Friedman 2000; Agoris et al. 2005). The idea is to take a sample from insulation oil and use several techniques to detect if there are forming gases in it. As a result, it helps to detect the faults in their incipient stage (Nejedly & Potacek 2009). The measured gases are called as the key gases (IEEE C37.91) and they are presented in the Table 3.1.

Table 3.1 DGA Key Gases (IEEE C37.91)

Symbol	Name
H_2	Hydrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
C_2H_6	Ethane
C_2H_4	Ethylene
C_2H_2	Acetylene
H_2O	Water (moisture)

DGA detects these gases from transformer oil. There is no clear consensus about the absolute maximum levels that are acceptable for each gas or their combination (Grisaru & Friedman 2000; CIGRE TB 445 2011). However, IEC 60599 determines the directive limits for each gas, which are presented in the Table 3.2.

Table 3.2 DGA Key Gas Concentration Limits (IEC 60599).

Gas	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Amount of Gas [ppm]	50 - 100	400 - 600	3,800 - 14,000	30 - 130	20 - 90	60 - 280	2 - 20

These limits are typical gas concentration values in oil in power transformers from about 25 electrical networks worldwide including more than 20,000 power transformers. All the power transformers are considered as individuals, and, therefore, the absolute gas values are not the most important thing. There are some transformers known to have considerably higher gas content than other similar transformers, yet they have been in service for many years without failure (CIGRE TB 445 2011). The increase of the gas levels are usually telling about the change in power transformer conditions and its functionalities. The Table 3.3 presents this.

Table 3.3 DGA Key Gas Concentration Annual Increase Limits (IEC 60599).

Gas	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Increase of Gas [ppm / a]	35 - 132	260 - 1060	1,700 - 10,000	10 - 120	5 - 90	32 - 146	0 - 4

Table 3.3 tells that although the absolute limit value has not been reached, the increase of the gas values can still inform about the upcoming failure. For this reason, the interpretation of the DGA report has to be considered not only the absolute values for individual gas concentrations, but also their rate of rise over time (CIGRE TB 445 2011).

According to IEEE C57.143, also the relative quantities (ratios) of the gases are considered as highly important besides their forming speed and absolute values. While the concentration may reveal that there is an upcoming failure, the ratios usually reveal its type. In order to calculate the ratios, the absolute values are also needed. The Figure 3.5 presents an example of the gas concentration levels measured by an online DGA monitor.

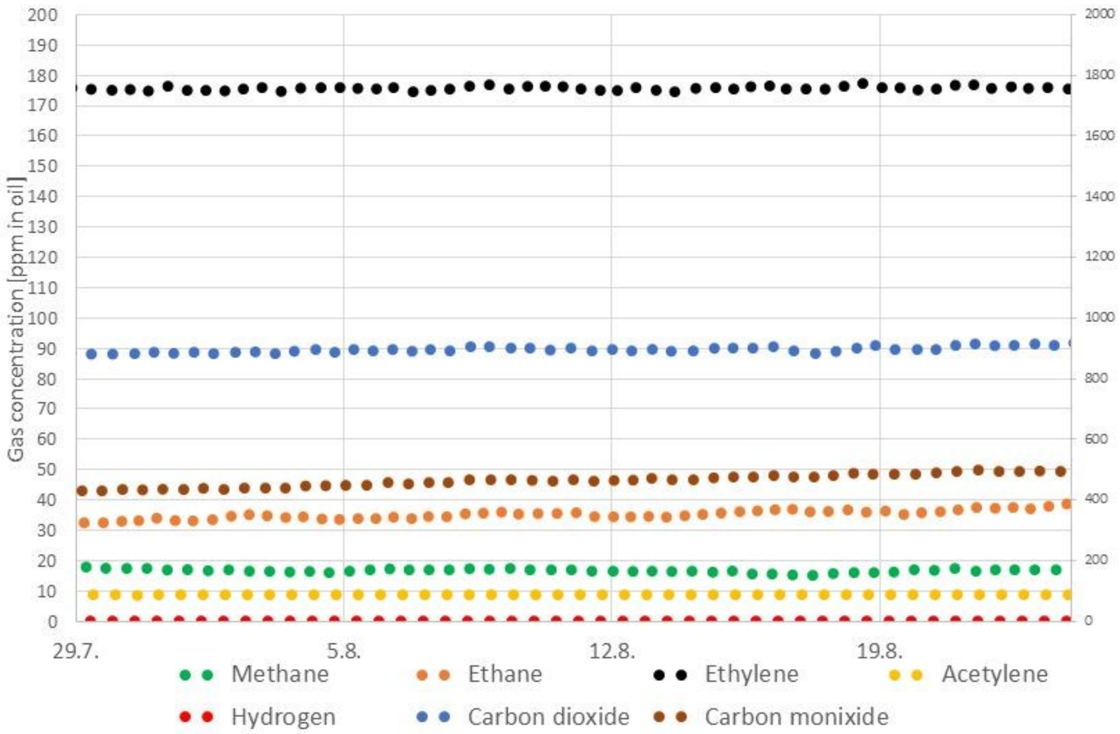

Figure 3.5 Online DGA Key Gas Concentration Measurements.

In the Figure 3.5 the carbon dioxide levels are in the right side axis while all the other gas levels can be interpreted from the left. The most common tool for finding the failure location is called as Duval triangle (IEEE C57.139). The triangle is presented later in the Figure 3.6 and the use of it requires information about the gas levels, especially C_2H_2, CH_4 and C_2H_4. The values can be noted from the Figure 3.5 and the ratios can be calculated with the equations 2, 3 and 4.

$$CH_4\% = \frac{CH_4}{C_2H_2+CH_4+C_2H_4} \cdot 100\ \%\ , \tag{2}$$

$$C_2H_4\% = \frac{C_2H_4}{C_2H_2+CH_4+C_2H_4} \cdot 100\ \%\ \text{ and} \tag{3}$$

$$C_2H_2\% = \frac{C_2H_2}{C_2H_2+CH_4+C_2H_4} \cdot 100\ \%\ , \tag{4}$$

CH_4 The absolute amount of methane,
C_2H_4 The absolute amount of ethylene,
C_2H_2 The absolute amount of acetylene.

With the values from the Figure 3.5 and with these equations the following Table 3.4 can be built, which presents the ratios for Duval triangle.

Table 3.4 Ratios for the Duval Triangle.

Symbol	Value	Ratio
CH_4	18 ppm	8.9%
C_2H_4	175 ppm	86.2%
C_2H_2	10 ppm	4.9%

From the Table 3.4 the ratios can be plotted to the Duval triangle which reveals the failure location. This is presented in the Figure 3.6. Each DGA sample can be plotted on the triangle as a dot whose location is determined by the ratios of those three gases. The triangle is subdivided into zones that are related to common fault types which are later presented in the Table 3.5.

The Duval triangle visualizes the basic types of faults. With these gas levels, it is possible to recognize the reason for a failure in a power transformer, and execute the necessary maintenance activities in order to prevent the major failures from happening. (IEEE C37.91; Duval 2016b) Therefore the gain from reduction in major faults will be somewhat attenuated by increase in minor faults or predictive maintenance actions. (IEEE C57.143)

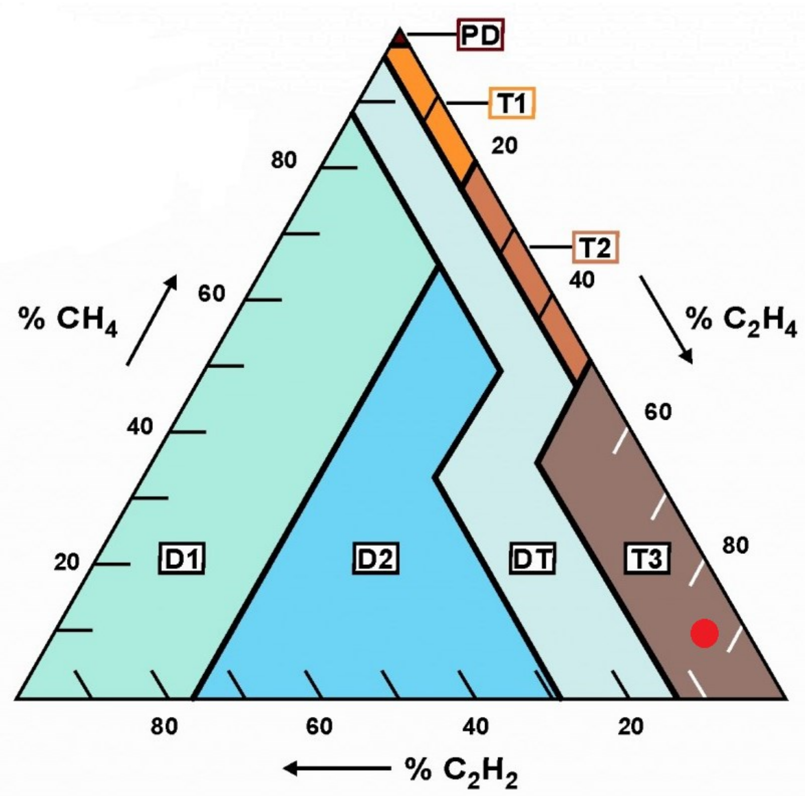

Figure 3.6 Duval Triangle (DGA Experts 2016, modified).

As seen from the Figure 3.6, the location of a plotted spot is in the right corner of the Duval triangle, which represents the failure type T3. Type T3 is presented in the following Table 3.5.

Table 3.5 Power Transformer Failure Types (DGA Experts 2016, modified).

Abbreviation	Type of Failure
PD	Partial discharges
T1	Thermal fault, t < 300 °C
T2	Thermal fault, 300 °C < t < 700 °C
T3	Thermal fault, t > 700 °C
D1	Discharges of low energy
D2	Discharges of high energy
DT	Mix of thermal and electrical faults

As seen in the Table 3.5, there are altogether seven different failure types. These cover all the possible failures which can be recognized with the DGA monitoring.

Also other methods for the failure recognition exist (Duval 2016b). However, they are not as advanced or accurate as Duval triangle. Other most common methods are called as Roger’s ratio and Dornenburg ratio. Also there are limit values for CO_2 / CO ratios and the method called Duval pentagon, but they have not been standardized yet.

The DGA monitoring should be made periodically by manual or automatic methods. These methods are covered in the following sub-chapters. Usually not just one method is chosen by the asset owner, but instead, both of the methods are used simultaneously. According to IEEE C57.143, an extra, unscheduled, oil sample is usually taken for laboratory analysis after an alarm is reported to confirm the result of the online monitor.

3.6.1 DGA Offline Monitoring

DGA offline monitoring, also called as manual DGA or laboratory DGA (Duval 2016b), is widely in use all around the world with power transformer owners. The idea is to manually take oil samples from the power transformer through the oil valves. Then the oil sample is taken to the laboratory where it is analyzed. The results are then sent to the asset managers who then decide whether some maintenance is required or not. (Nyman 2016) All the samples should be taken in accordance with ASTM D 923 or IEC 60567.

Offline monitoring is considered to be really accurate method what it comes to power transformer condition assessment in general. However, there are also risks and cons in it. First, there is a chance that the technician, who is taking the actual oil sample, does a mistake or handless the sample carelessly and the sample gets contaminated. Naturally the laboratory results are not correct after that anymore because even the most sophisticated diagnosis methods cannot overcome faulty samples (IEC 60567). Second, the offline oil sample and analysis is usually done once or twice in a year, and sometimes even more infrequently (Duval 2016b). That means that failures which are evolving faster than the sampling interval, will not get detected which increases the risk of the power transformer to fail.

3.6.2 Online DGA Monitoring

Another method for DGA is online monitoring which is part of the CBM strategy. It is a real-time method that continuously gives instant information about the power transformer. With suitable sensors, the diagnostic measurement can be attached to the network automation system and, when any kind of abnormal measurement results is detected, the information goes directly to control room or asset manager (Nousiainen 2015; IEEE C57.104; Aro et al. 2011).

The online DGA monitor data traffic, wired connection is the most common one because utilities typically has their own closed networks. Nowdays the wireless connection is new increasing trend together with communication over internet and cloud services. However, this is still quite limited because of the security concerns the utilities are having. (Leivo 2016)

The online DGA monitoring is usually used with the most expensive and important power transformers (Nousiainen 2015; Duval 2016b). The idea is similar than with the offline method, but instead of taking oil samples manually once in a year, the online monitor takes and analyses them automatically in, for example, every hour, making it possible to detect failure which develop rapidly (Breckenridge et al. 2002). It is the most advanced method to give detailed information about the power transformer conditions (Duval 2016b).

There are also few concerns in the DGA monitors. First, if the power transformer or the substation is old or it is in the remote area, there is not always suitable couplings or data connections available. This means that the asset owner should invest more capital to attach the monitor and to build the data-infra. Also, there might be failures which can evolve in the matter of minutes (Aro et al. 2011). In those cases the online DGA monitor cannot detect them.

The Vaisala online DGA monitor is presented in the Figure 3.7.

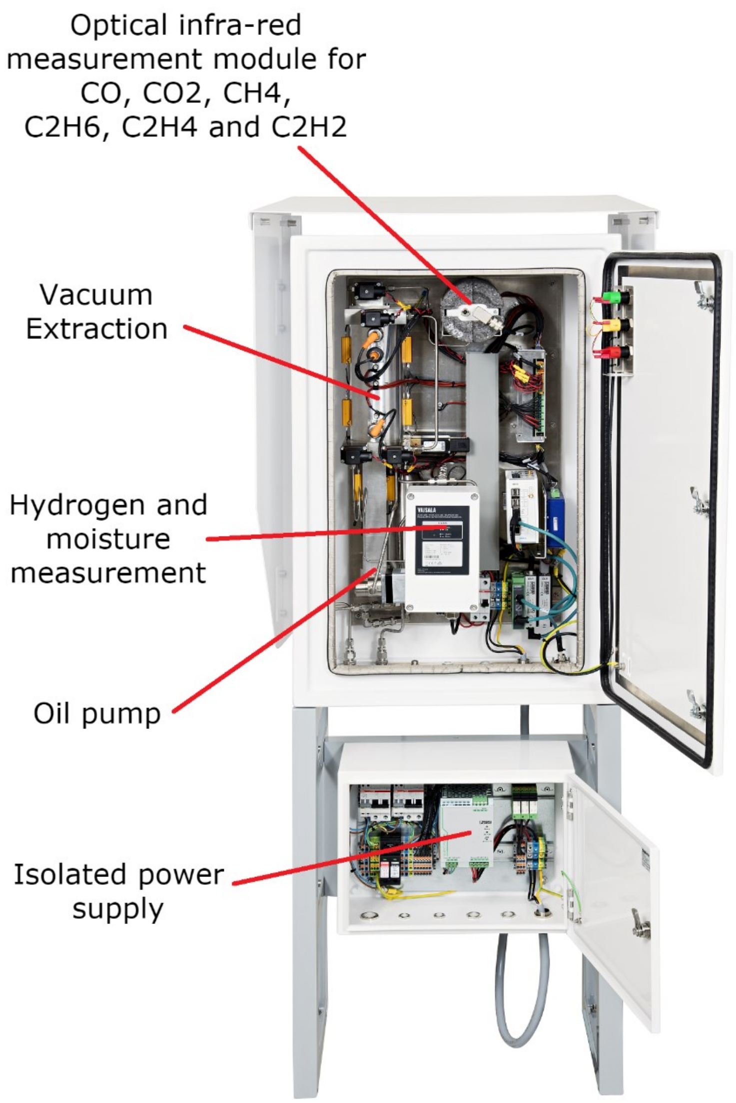

Figure 3.7 Vaisala Optimus™ DGA Monitor (internal source).

The online DGA monitor has to be able to operate in extreme conditions and provide stable long-term measurements. Vaisala's online DGA monitor first measures hydrogen and moisture levels directly in oil phase. After that the oil sample is pumped into vacuum extraction chamber where the gases are separated from the oil. Then the extracted gas-mixture is compressed into optical measurement module, where the rest of the gases are measured with infrared technology. Then the oil is returned back to the power transformer and next measurement cycle can begin. As an end-result, dependable real-time monitoring data is available for asset owner management. (Leivo 2016)

3.7 Condition Monitoring in Different Companies

The maintenance actions can be planned yearly. It is known that the maintenance practices may be significantly different between countries and even between companies.

The possible factors that may influence maintenance practices are:

- transformer characteristics and specifications,
- the quality of the components installed on the transformer,
- the used load of the transformer,
- the transformer environment,
- historical transformer failure rate and types,
- the failure mode and its effects on substation safety,
- company culture and focus on maintenance,
- the availability and costs of labor and
- the presence of a maintenance optimization program. (CIGRE TB 445 2011)

Condition monitoring and maintenance depends also on the importance of a power transformer in the grid. (Khoshrou 2016; Nyman 2016) Nowadays DGA analysis is common, but some companies still do not understand how to interpret the results and do the necessary maintenance actions (Sparling 2016).

3.7.1 Generation Companies

Power transformers used in power generation are usually rated with same nominal power as the generator. In nuclear power stations the loading rate is usually 90 – 95 % all the time, so they are always being run by their full capacity (Härmälä et al. 2016). Therefore some companies are taking the oil samples more often than lightly loaded asset owners. The sampling interval is usually from 3 months to 2 years (Khoshrou 2016; Härmälä et al. 2016; CIGRE TB 445 2011) while visual inspections are done from daily to 12 months (CIGRE TB 445 2011).

The voltage levels in GSU transformers are usually 10.5/220 kV and 20/400 kV (Elovaara & Haarla 2011a). In case of a failure, some companies have a spare transformer in their own storage nearby the primary transformer. Taking it into use can take 1 to 2 weeks. (Härmälä et al. 2016)

3.7.2 TSOs

The offline oil sampling interval is usually once or twice in a year (Khoshrou 2016) so it is usually longer than with GSU transformers. TSO substations are divided all over, so online monitoring is important thing because it is not possible to have site visits for maintenance or oil sampling very often. If the online DGA monitor is installed, the offline sampling interval is often decreased to 1 per year instead of 2. (Ojanen & Mertanen 2016b) The most critical units are equipped with online monitors in almost 50 % of the cases (CIGRE TB 445 2011).

The voltage level in TSO grids are usually 400/220 kV but, for example, in China there are already 1100 kV voltages in use (Elovaara & Haarla 2011a). So the nominal power for TSO can be anything up to 1000 MVA or even more. Because of such a big power, all the TSO power transformers should be considered as highly critical. However, in practice, all the grids and power transformer locations are planned at least with N-1 criterion (Pyykkö 2015). The N-1 is covered later in this thesis.

3.7.3 DSOs

Offline sampling in DSO power transformers is an industry standard. The sample is taken and analyzed usually once or twice in a year (Piironen 2015b), so it is quite similar with TSOs. Online DGA monitoring is, however, not so common because of the relatively high price of the monitor compared to actual DSO transformer. Sometimes the online monitor can be more expensive than the actual transformer which it is measuring (Khoshrou 2016).

The voltage levels of DSO power transformers are usually 110/20 kV (Elovaara & Haarla 2011a). However, some of them can be as critical as TSO units if there is only one transformer on a substation (Piironen 2015a). Also in urban areas, most of the DSO transformers are considered as critical ones because there are lot of electricity consumption (Pyykkö 2015). Similar to TSO networks, some DSO grids are planned with N-1 criterion as well.

3.7.4 Industry Companies

Ojanen & Mertanen (2016b) mention that industrial power transformers are usually not maintained so systematically. In factories people often may not understand the importance of the transformer and that the whole production can depend on it. All of these transformers are highly critical, because often there is only one unit which covers the whole factory and its production.

Basic maintenance actions, which requires the planned outages, are usually not done at all in general, because 2 weeks lost production, is considered to be too much. The actual condition of a power transformer may not be known by anyone at all (Pyykkö 2015). In some factories, however, some offline sampling is done. But, depending on a transformer, they are taken once between every 6 months to 10 years (Alatalo 2016).

4. POWER TRANSFORMER FAILURE RISK REDUCTION AS THE RESULT OF ONLINE DGA MONITORING

A major failure is usually understood as a failure leading to a removal of the unit from its base. IEEE C57.143 states that the catastrophic transformer failure is the proportion of failures causing fire or tank rupture with probable damage to peripheral equipment.

The only major international surveys on large power transformer failures are Bossi et al. (1983) and CIGRE TB 642 (2015). In this thesis the CIGRE TB 642 (2015) is considered to be the main source of information as it collects 964 major failures which occurred between 1996 and 2010 within a total population of 167,459 transformer-years. Altogether there were 22,181 substation power transformers 1,703 GSU power transformers from 22 countries and 56 utilities. The manufacturing year of the units vary between 1950's to 2009.

4.1 Power Transformer Failure Risk

Power transformer failure risk evaluation requires good condition assessment techniques. Moreover, utilities usually track transformer outage data as outage reasons, frequency, duration and consequences. This had resulted in establishing baselines, determining target levels of performance, highlighting trends and identifying those components that require focused corrective action. Moreover, as transformer failures are relatively rare, benchmarking can provide the critical mass required for analysis.

A risk is quantity associated with an unwanted event that may or may not occur. Characteristic for risk is that uncertainty is involved. The risk is the product of the probability of an event and its consequences. According to CIGRE TB 422 (2010), risk assessment attempts to answer the following fundamental questions:

- What can happen and why?
- How likely are they to occur?
- What are the consequences?

Mathematically, the risk can be defined with the equation 5:

$$RISK = PROBABILITY \cdot CONSEQUENCE. \tag{5}$$

The consequence can be also seen as the criticality of the power transformer (CIGRE TB 541 2013). After this kind of calculations are made, the asset manager has to decide if the level of the risk is acceptable or does it require further evaluation.

4.1.1 The Failure Rate

There is very limited literature available discussing failure statistics of power transformers. The studies that exist, do not always provide consistent definitions for failures and, therefore, lots of conflicts in published data and in expert opinions can be found (Bossi et al. 1983). In order to have a true comparison between the failure data, it would require that the failure definitions are similar.

The failure rate is the most utilized measure of reliability because it is based on the count of the number of failure which should be easily obtainable. The failure rate of a single population is defined as

$$\lambda = \frac{n_1 + n_2 + .. + n_i}{(N_1 + N_2 + .. + N_i) \cdot T} \cdot 100\ \%, \tag{6}$$

λ *The failure rate of a single power transformer population,*
n_i *Number of failure in i-th year,*
N_i *Number of power transformers operating in i-th year,*
T *Reference period (normally one year)*. (CIGRE TB 642 2015)

The equation 6 assumes that the reference period is same for all the power transformers.

It is also possible to calculate the combined failure rate of different populations, which is used in this thesis. In this cause it is postulated that the number of operating transformers is constant during the reference period.

$$\lambda = \frac{n_1 + n_2 + .. + n_i}{N_1 \cdot T_1 + N_2 \cdot T_2 + .. + N_i \cdot T_i} \cdot 100\ \%, \tag{7}$$

λ *The failure rate of different power transformer populations,*
n_i *Number of failure by i-th population,*
N_i *Number of power transformers of i-th population,*
T_i *Reference period of i-th population*. (CIGRE TB 642 2015)

Without clear definitions, making comparison becomes difficult. The following factors constrained the available statistics:

- limited publicly available reliability statistics,
- the majority of the surveyed studies did not provide failure definitions,
- where failure rates were given, the majority of the sources did not provide the formula used for calculations,

- the majority of the studies did not provide the manufacturing period of the failed units,
- the maintenance philosophies, design specifications, condition monitoring practices and operating condition are different in target countries and
- the studies did not use same categorization of transformers according to application. (CIGRE TB 642 2015)

However, there are multiple articles about the power transformer failure rates. The results of them are listed in the Table 4.1.

Table 4.1 Failure Rates from Surveys from 1968 to 2005 (CIGRE TB 641 2015).

Survey	Application / Classification	Failure Period	Manufacturing Period	Failure Rate (%)
Cigrè International survey	All voltage levels (60 - 700 kV)	1968 - 1978	Pre 1978	2
United Kingdom	All voltage levels	Pre 1987	Pre 1987	< 2
United Kingdom	GSU, Major failures	1974 - 1995	Pre 1995	1.2
ZTZ Service Database, Ukraine	GSU, TSO, Rater power >= 100 MVA	2000 - 2005	Pre 2005	1 - 2
US-NGRID, United States	Distribution 115 kV & <= 69 kV	-	-	0.35 - 0.8
Hydro Quebec, Canada	All voltage levels, major failures	-	-	< 0.5
American Electric Power	345 kV & 765 kV	Pre 1986	Pre 1986	1.3 - 2.9
American Electric Power	345 kV & 765 kV	Post 1986	Pre 1986	0.35 - 1.35
Australia & New Zealand	Costly failures	Pre 1996	Pre 1996	0.4

As the Table 4.1 shows, the failure rate varies a lot depending on a research, power transformer application, failure period and manufacturing period. However, it can be said that the failure rate is usually between 0.5 % and 3.0 %.

The failure rates of combined population were calculated with the equation 7. Because the number of operational transformer was only provided once for one year, the total number of transformer-years was calculated under the assumption that the number of transformers in operation was constant during the reference period. It is important to notice that the number of failures of GSU units and units in voltage classes above 500 kV, as well as the population of these two categories, was low. Those failure rates should thus be considered with caution.

The following Tables present the failure rates of power transformers in different use.

Table 4.2 Failure Rates of Substation Power Transformers (CIGRE TB 642 2015).

Failures & Population Information	**Highest System Voltage [kV]**						
	69 <= kV < 100	**100 <= kV < 200**	**200 <= kV < 300**	**300 <= kV < 500**	**500 <= kV < 700**	**kV >= 700**	**All**
Major Failures	144	280	186	152	27	10	799
Transformer-Years	15267	64718	37017	25305	4774	2991	150072
FAILURE RATE	**0.94%**	**0.43%**	**0.50%**	**0.60%**	**0.57%**	**0.33%**	**0.53%**

The Table 4.2 presents that the failure rate of substation transformers varies between 0.33 % and 0.94 % when the overall failure rate is 0.53 %.

Table 4.3 Failure Rates for GSU Power Transformers (CIGRE TB 642 2015).

Failures & Population Information	**Highest System Voltage [kV]**						
	69 <= kV < 100	**100 <= kV < 200**	**200 <= kV < 300**	**300 <= kV < 500**	**500 <= kV < 700**	**kV >= 700**	**All**
Major Failures	0	20	43	89	9	4	165
Transformer-Years	153	3278	4639	6740	1837	740	17387
FAILURE RATE	**0.00%**	**0.61%**	**0.93%**	**1.32%**	**0.49%**	**0.54%**	**0.95%**

The Table 4.3 presents that the failure rate of GSU transformers varies between 0 % and 1.32 % when the overall failure rate is 0.95 %.

The data from the presented Tables has been collected to the Figure 4.1.

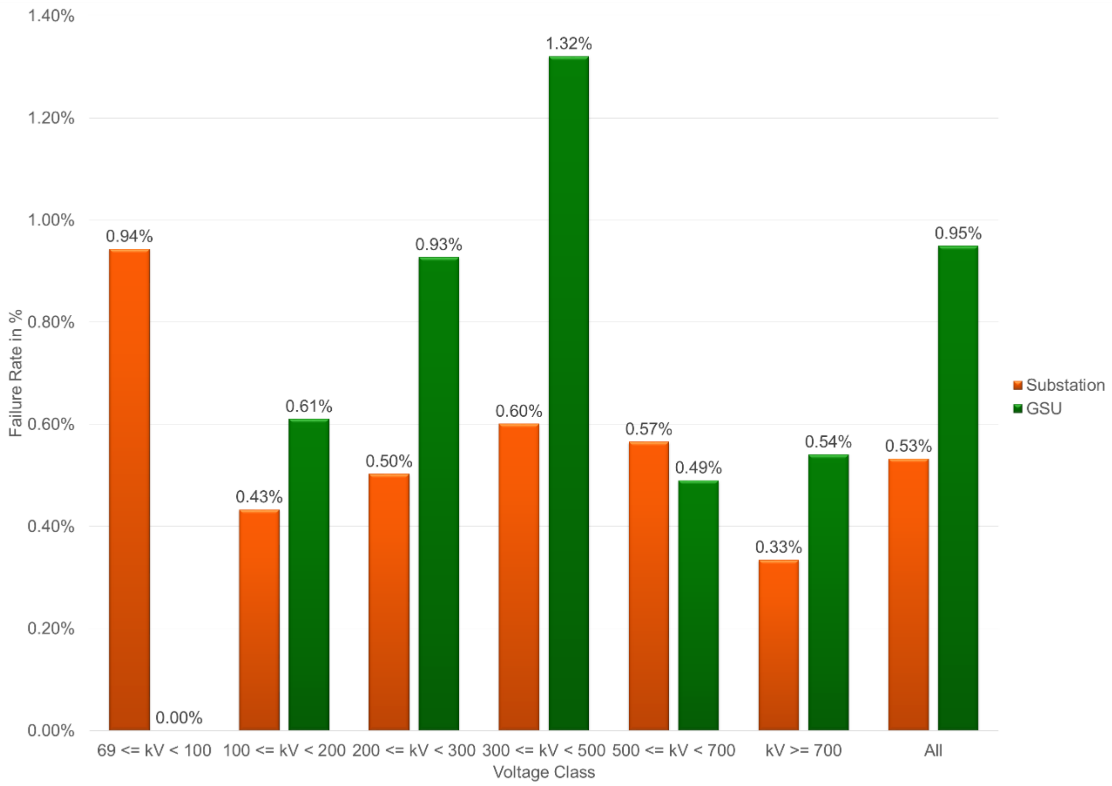

Figure 4.1 Failure Rate Dependent on Voltage Level.

The Figure 4.1 shows the differences between the failure rates of substations and GSU transformers. Also the overall values are included. According to CIGRE TB 248 (2004), the failure rate of 0.5 % is considered to be good, 1 % satisfactory, 1.5 % fair, 2.0 % poor and 3.0 % unacceptable.

It is important to understand that failure rates varies greatly and presented values are averages from the whole population. The load rate, used maintenance strategy, lightning strikes, falling trees and animals has a big effect on failure rates (Boman 2016). Also, the experienced historical fault rate may not be relevant for a component reaching the end of its life (CIGRE TB 248 2004).

4.1.2 Failure Modes

Failure mode refers to the manner in which the failure occurred. There are five different failure modes: dielectric, electrical, thermal, physical chemistry and mechanical mode. The failure mode analysis of substation and GSU transformers according to voltage class is shown in the Table 4.4. The data is based on the same 964 power transformers that were presented in the sub-chapter 4.1.1.

Table 4.4 Failure Mode Analysis Dependent on Voltage Class (CIGRE TB 642 2015).

Failure Mode	Highest System Voltage [kV]						
	69 ≤ kV < 100	100 ≤ kV < 200	200 ≤ kV < 300	300 ≤ kV < 500	500 ≤ kV < 700	kV ≥ 700	All
Dielectric	70.14%	25.33%	26.68%	24.89%	72.22%	42.86%	36.62%
Electrical	12.50%	19.33%	15.72%	17.84%	0.00%	25.57%	16.49%
Thermal	0.69%	12.00%	10.04%	18.25%	2.78%	0.00%	10.89%
Physical Chemistry	0.00%	3.66%	4.37%	4.56%	2.78%	0.00%	3.32%
Mechanical	6.25%	27.33%	22.71%	18.25%	11.11%	7.14%	20.02%
Unknown	10.42%	12.33%	10.48%	16.18%	11.11%	21.43%	12.66%

As presented in the Table 4.4, the dielectric failures are the most prominent, followed by mechanical and electrical failures. The same information is presented in the Figure 4.2.

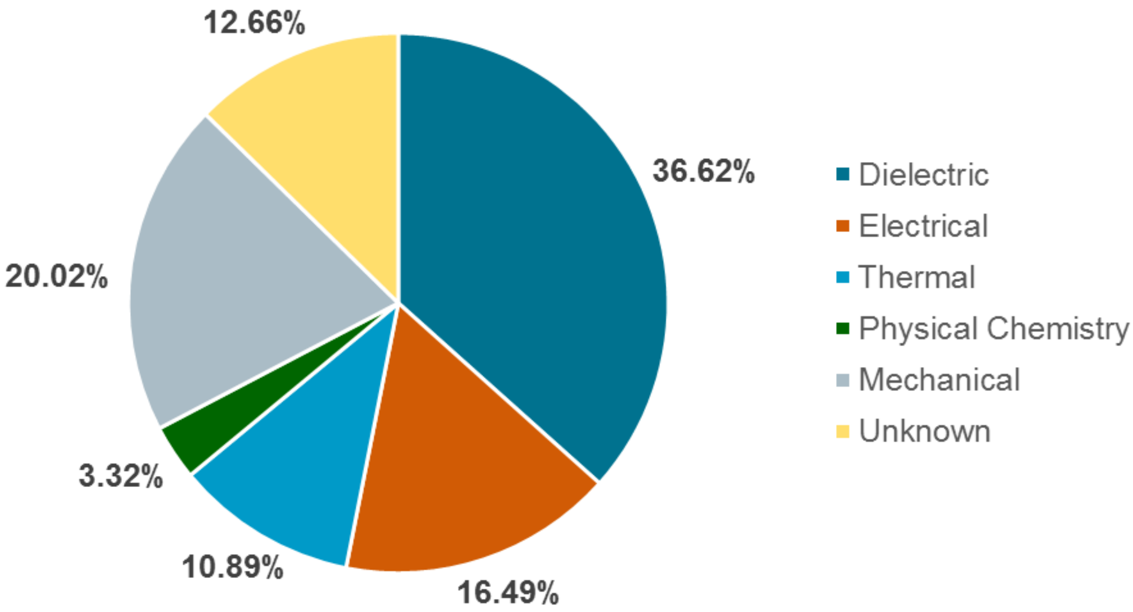

Figure 4.2 Failure Mode Analysis.

The Figure 4.2 sums the failure modes. It clearly shows that the dielectric, mechanical and electrical failures are the most common ones. There are some variation in failure mode rates between substation transformers and GSU transformers which is discussed is CIGRE TB 642 (2015) and in Khoshrou (2016).

4.1.3 The Failure Locations

Similar than with the failure rates, several studies exist about the failure locations and there is no clear consensus about them. Different studies show different results (Smekalov et al. 2002; Blanc et al. 2008; Vahidi & Tenbohlen 2014), but the CIGRE TB 642 (2015) can be considered as the most comprehensive one also in this one.

The failure data of the population was analyzed and the primary failure locations were initiated. In the Table 4.5 the location analysis is shown according to voltage class of substations and GSU transformers. The data is based on the same 964 power transformers that were presented in the sub-chapter 4.1.1.

Table 4.5 Failure Location Dependent on Voltage Class (CIGRE TB 642 2015).

Failure Location	Highest System Voltage [kV]													
	69 ≤ kV < 100 (144)		100 ≤ kV < 200 (300)		200 ≤ kV < 300 (229)		300 ≤ kV < 500 (241)		500 ≤ kV < 700 (36)		kV ≥ 700 (14)		All (964)	
Winding	109	75.7%	107	35.7%	75	32.8%	79	32.8%	4	11.1%	4	28.6%	378	39.2%
Lead Exit	1	0.7%	7	2.3%	16	7.0%	20	8.3%	2	5.6%	4	28.6%	50	5.2%
Insulation	2	1.4%	4	1.3%	6	2.6%	6	2.5%	0	0.0%	1	7.1%	19	2.0%
Electrical Screen	0	0.0%	0	0.0%	0	0.0%	3	1.2%	0	0.0%	0	0.0%	3	0.3%
Bushing	0	0.0%	32	10.7%	33	14.4%	44	18.3%	5	13.9%	1	7.1%	115	11.9%
Core and Magnetic Circuit	7	4.9%	7	2.3%	10	4.4%	4	1.7%	2	5.6%	0	0.0%	30	3.1%
Flux Shunts	0	0.0%	0	0.0%	0	0.0%	3	1.2%	0	0.0%	0	0.0%	3	0.3%
Tank	0	0.0%	1	0.3%	0	0.0%	2	0.8%	0	0.0%	1	7.1%	4	0.4%
Cooling Unit	0	0.0%	3	1.0%	1	0.4%	2	0.8%	2	5.6%	0	0.0%	8	0.8%
Tap Changer	3	2.1%	84	28.0%	57	24.9%	38	15.8%	3	8.3%	0	0.0%	185	19.2%
CT	0	0.0%	1	0.3%	1	0.4%	0	0.0%	0	0.0%	0	0.0%	2	0.2%
Unknown	22	15.3%	54	18.0%	30	13.1%	40	16.6%	18	50.0%	3	21.4%	167	17.3%

The Table 4.5 reveals the percentages of different failure reasons. It shows that the biggest reasons are windings, which causes 39.2 % of the failures, tap changers with 19.2 %, unknown reasons with 17.3 % and bushings with 11.9 %. Other locations can be considered as minor locations. The information from the Table 4.5, excluding the data from 69 – 100 kV units because of its significant emphasis on windings, is presented in the Figure 4.3.

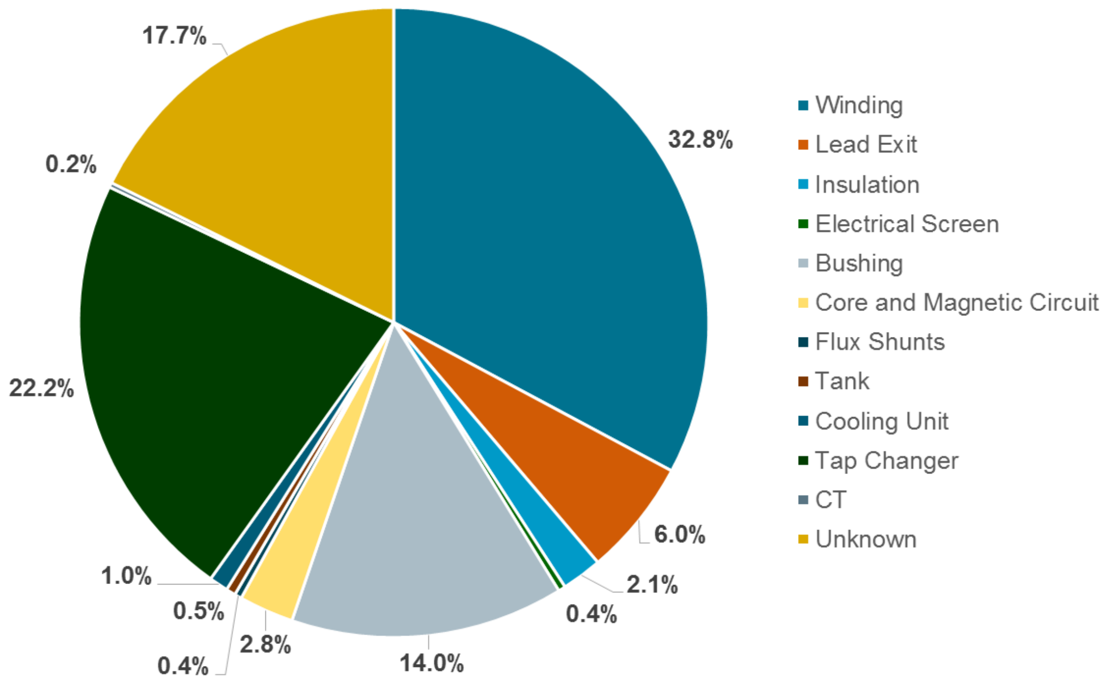

Figure 4.3 Failure Location Analysis for 820 Major Failures.

The Figure 4.3 presents the failure location analysis based on 820 major failures. Under 100 kV voltage failures were excluded from the graph because of their different failure location behavior. The Figure shows clearly that windings, tap changers and bushings are the main locations for failures.

According to CIGRE TB 642 (2015), the failure locations are different between substation and GSU transformers. The most common reason for failures are windings in both transformer types. GSU transformers had a higher share on windings and lead exits, while substation transformers failures usually are the consequence of the problems in tap changers. The contributions of bushing related failures are similar in both transformer applications. However, even that the failure location varies between the application and age distribution, all of those fault types can be found and prevented or at least diminished with online DGA monitoring.

4.1.4 External Effects of the Failure

When major failures occur, external damages may happen. The Figure 4.4 presents this. All the 964 major failures from CIGRE TB 642 (2015) were used to do this statistic.

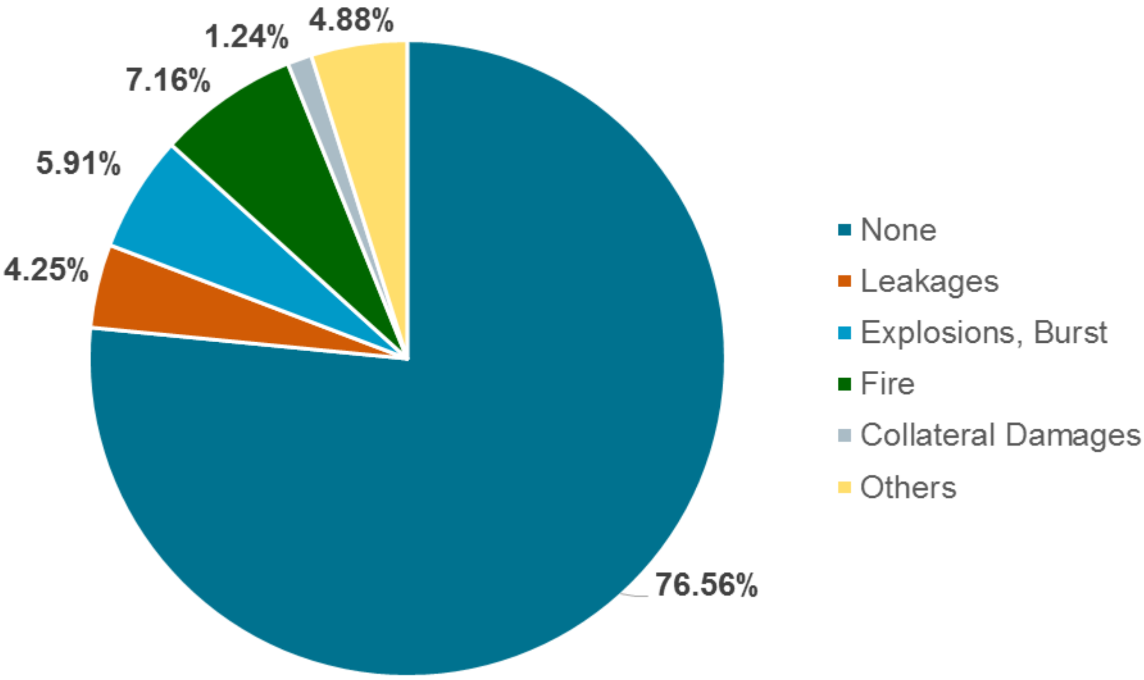

Figure 4.4 External Effects on Major Failures (CIGRE TB 642 2015).

As seen in the Figure 4.4, in most of the cases (76.6 %) the failures did not cause any external effects. The most problematic situation after a major failure were fires and explosions with 7.1 % and 5.9 % percentages. Together they form about 13 % of the external effects. From this number, 10 % can be considered to be catastrophic. This 1.3 % share from all the failures is used later in this thesis as a rate of catastrophic failures.

4.1.5 The Failure Duration

The duration of an outage caused by a failure varies a lot. Basically it can be anything from hours to years. The duration depends on a type and seriousness of the failure. Usually there are a few options which determines the duration: onsite repair, repair on workshop and scrapping. This is presented in the Figure 4.5. All the 964 major failures were considered in this statistic.

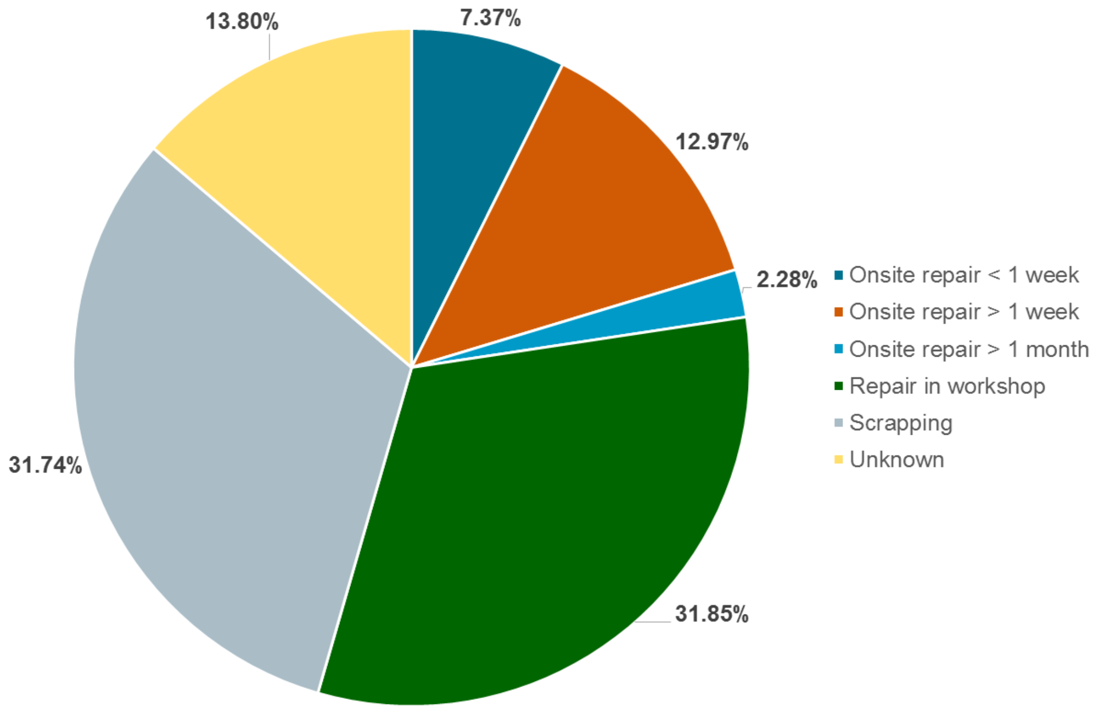

Figure 4.5 The Actions Taken After Major Failures (CIGRE TB 642 2015).

The Figure 4.5 visualizes that the repair in workshop is the most common action for a major failure. Also the scrapping and renewal of the power transformers is really common. Onsite repair with different durations also happen.

4.2 Online DGA Monitoring Impact to the Failure Rate

Slowly developing faults occur in most cases over periods of months or years. Already existing methods, including the offline DGA, are adequate to detect such faults only if the timing with the oil sampling is right (Duval 2016b). Online monitors increases that number a lot (Boman 2016; Ojanen & Mertanen 2016b), but, however, those failures occurring rapidly in minutes cannot be detected by any device (Duval 2016b). Also, it is important to notice that sometimes it is not possible to avoid failures, but with the online DGA monitoring it is possible to recognize them in advance and minimize the actual downtime by preparing to it (Ojanen & Mertanen 2016b). The Figure 4.6 presents the failure rate with and without online DGA monitoring on substation transformers.

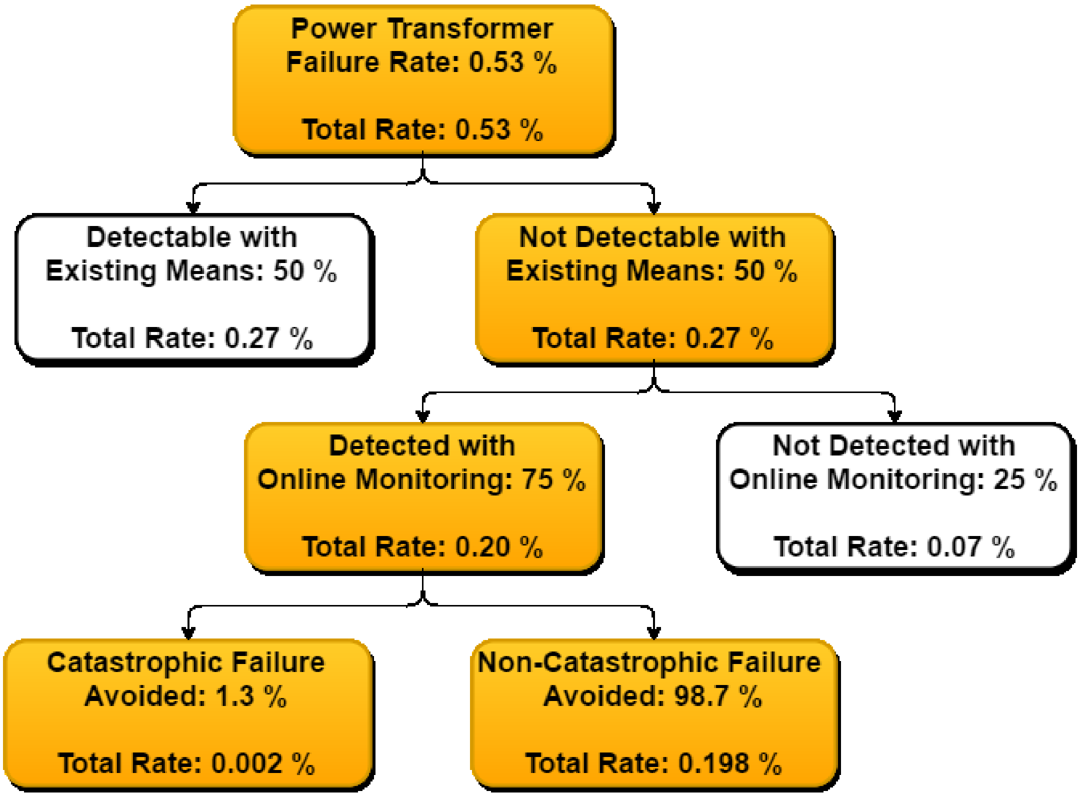

Figure 4.6 Failure Rate Reduction With Online DGA Monitor.

The following list describes the logic of the Figure 4.6.

- The average failure rate for a substation power transformer is 0.53 % (CIGRE TB 642 2015).
- Already existing methods can detect 50 % of the failures while another 50 % of the failures cannot be detected by already existing methods.
- Online DGA monitor can detect 75 % from the rest of the failures while 25 % cannot be detected. It is unrealistic to expect 100 % coverage, and also some failures are instantaneous by nature and may occur extremely rapidly.
- The catastrophic failure rate is considered to be 1.3 % of the total failures and the non-catastrophic failures form the 98.7 % of the total failures. (Duval 2016a)

It is useful to distinguish between non-catastrophic and catastrophic failures since their economic consequences are quite different. This example shows that with the DGA monitor it is possible detect 87.5 % of all possible failures, while without the online monitoring the number is 50 %. The result is that the online DGA monitor improves the rate by 75 % which can be considered as remarkable improvement.

5. FACTORS AFFECTING INVESTMENT DECISIONS

The investment and its focusing and timing is always a complex optimization task. According to Lakervi & Partanen (2008), an individual investment decision usually causes an investment program. In the program, the main concern is the economic development of the grid, and without the clear vision about the future plans, the annual development program is difficult to establish.

Especially transmission grid investments are expensive and time consuming. Therefore, it is crucial to plan the investments carefully, so that the resources are used with the best possible way. As Elovaara & Haarla (2011a) state, the planning includes the comparison of different possibilities and their economy and technical reviews.

The total customer value of the online DGA monitor is realized when it actually prevents the power transformer failure from happening. This Chapter describes the economic value of the online DGA monitor with actual monetary terms.

5.1 Investment Decision Making

Power transformers are critical to power system performance, reliability of supply and to the financial performance and economic profitability. Their technical complexities together with high costs and long life expectancy form unique decision making challenges to asset managers. The decision making commonly includes trying to balance business returns against strategic investment decisions and industry and technology changes (IEC 2015). Given the long-term nature of such an analysis, the metrics and evaluation criteria used by asset owners are critically important.

5.1.1 Decision Making Levels

The asset management decision making can be divided into three levels:

- strategic level,
- tactical level and
- operational level. (CIGRE TB 597 2014)

The asset management planning process is a top down process. Each of the different levels decide how much money under its control is spent for what and when. This is presented in the Figure 5.1.

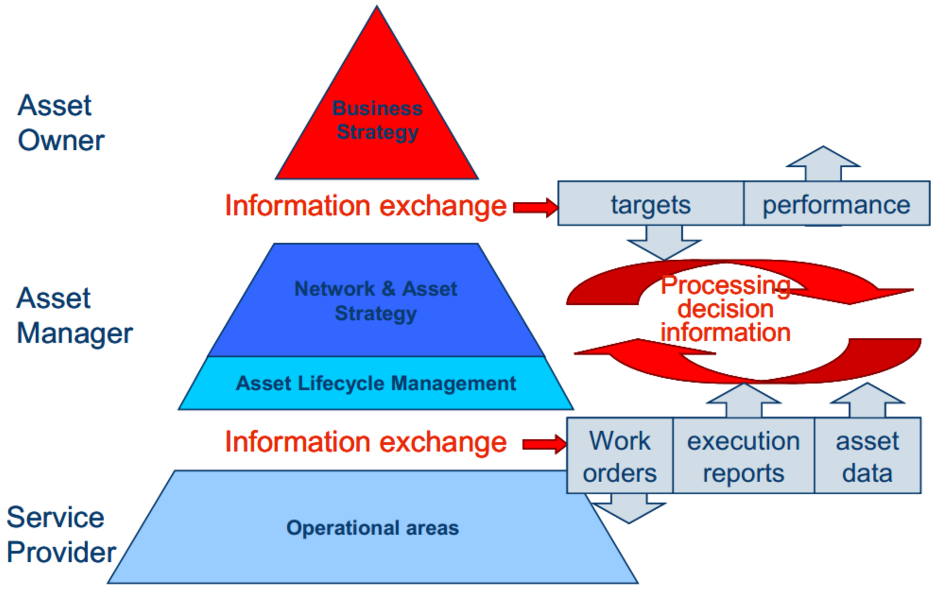

Figure 5.1 Decision Making Levels (CIGRE TB 597 2014, modified).

The Figure 5.1 presents the levels of the decision making, and, at the same time, the hierarchy of an organization. The upper level of the triangle grants a budget to a lower level, and therefore it is crucial to have their support to confirm the financing for new investments. The budgets are usually granted for a certain periods of time, so it is important to understand the timing when thinking about the investments.

CIGRE TB 597 (2014) states that the strategic level is planned to give long-term guidance in corporate development, risk taking and new technology adaptation. At this level, the asset owner and the asset manager agree upon the overall planning and the basic strategic development with respect to the corporate policy. The plan sets high level performance objectives and critical constraints in the form of risk tolerance policy.

Once approved, the strategic plan is transformed into a medium-term plan at a tactical level. The tactical level gives objectives about grid development, equipment options and timing. Decision makers at this level evaluate the options available and the system requirements and, once this plan is approved, the budget is set for grid development and fleet management, such as condition monitoring. (CIGRE TB 597 2014)

Finally, the operational level optimizes how to spend the budget. It is a short-term action with budget and execution of development plans with given resources. On this level, the long-term plan is broken into single measures. Decisions on bundling and timing of measures are made. Knowing the condition and criticality of the assets is very helpful to prioritize the measures. (CIGRE TB 597 2014)

5.1.2 Decision Making Process

According to CIGRE TB 531 (2013), the decision making process often consists of the following main steps:

- identification of a need,
- risk assessment of the asset constraints,
- identifying alternatives for constraints forming a risk for the business,
- selection of preferred alternative through optimization analysis and
- making the actual investment.

The reliability indicators are important to understand while considering the risk. The key metrics is to understand how decision affects the reliability of the network. Therefore different companies work with different ways.

There are companies where an individual asset manager can make quite big investment decisions by himself. For example, it is possible to try new monitoring devices whenever wanted. This is usually the general principles in small DSOs or industrial companies, where there can be only a single person who is responsible on the power transformers (Ojanen & Mertanen 2016b) while some companies have a small group of managers who make the collective decision (Alatalo 2016).

Also heavier methods do exist. In some companies anyone can make a so called ‘action request’. A small group of managers then processes the request and if it is considered as ‘good’ action request, it goes forward to the board of directors. In some cases it is possible that the directors want to give the decision to the actual board of the company. Whenever the decision making goes this high level, very specific and detailed investment calculation are needed. (Härmälä et al. 2016; Ojanen & Mertanen 2016b)

When making the actual decision, the company has to consider several aspects. Some companies are prescribed to have a bidding for several OEMs. The main things, which defines the actual product, include suitability, user experience, price, origin and required maintenance. Also the *internal rate of return* (IRR) is usually calculated. (Härmälä et al. 2016) Decision making levels were presented in the sub-chapter 5.1.1. According to them, the support from upper management level is a fundamental thing when investing in monitoring devices. Sometimes the managers do not understand online monitoring or the power of the diagnostics in general (Fenton 2016). Therefore it is crucial to justify the investment other ways to get the funding.

5.2 Customer Value

Increasing customer expectations make product quality and customer value important strategic decisions. Customer value is the heart of business marketing strategy. It represents an overall perceptions of benefits received and sacrifices made. (Hutt & Speh 2013) The idea of it is presented in the Figure 5.2.

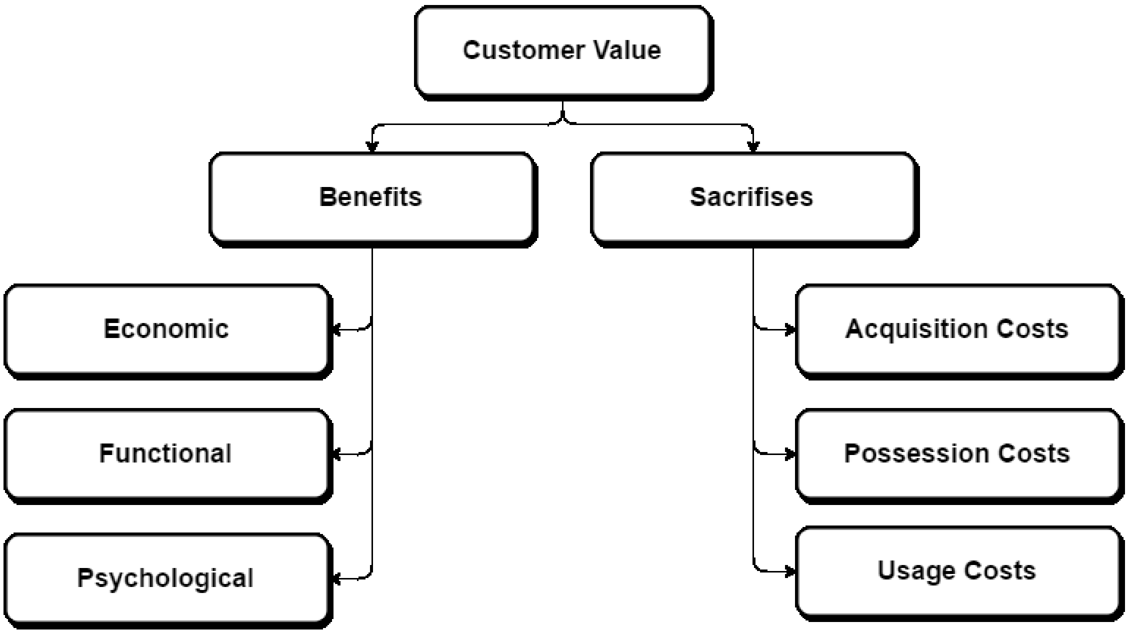

Figure 5.2 Customer Value (Hutt & Speh 2013).

As the Figure 5.2 presents the customer value consists of benefits and sacrifices. The benefits can be seen as what the customer gets. The benefits usually meet the basic needs of a customer, and some of them go beyond the basics and create added value in a buyer-seller relationship. Sacrifices can be understood as a total cost that the customer pays. These costs include the actual purchasing price, acquisition costs, such as delivery, and usage costs, such as maintenance costs. (Hutt & Speh 2013)

The customer value can be described with the following equation 8:

$$CUSTOMER\ VALUE = BENEFITS - SACRIFISES. \tag{8}$$

When thinking about the customer value, it is usually good to express it with monetary terms. However, at least some of the benefits, such as quality of the product, are usually difficult to express that way. Instead, a benefit such as saved time is usually easier task to express with euros. Altogether, with the “customer value mind-set” it is possible to calculate the minimum value needed from a single online DGA monitor to make it a profitable investment.

5.2.1 Total Benefits

The main benefits from online DGA monitoring are easy to understand. The benefits can be allocated to three levels, which were also presented in the Figure 5.2:

- economic,
- functional and
- psychological. (Hutt & Speh 2013)

In practice these mean cost savings and profitability, reliability, stress removal, peace of mind and other non-monetary factors. The total benefit is the sum of all of these.

As discussed in the sub-chapter 4.2, in order to evaluate the economic gain of an online monitor, it should be recognized that the existing devices and methods, such as gas relay and manual DGA sampling, will also detect some faults. Also there are instantaneous failures by nature which are not detectable by any monitoring device. In between there are fast evolving faults that cannot be detected with existing means but could be detected by suitable monitoring. These faults are the beneficial target for monitoring and failure resolution costs.

According to IEEE C57.143, the following events are the main parts of economic benefits of online DGA monitor:

- improved loading capacity,
- extended lifetime,
- reduced maintenance costs and
- reduced failure-related repair or replacement costs.

There are also a number of other benefits, as follows, that are tangible but cannot be quantified easily:

- improved planning for scheduled outages by using remote equipment condition assessment to avoid additional outages,
- enhanced financial results with performance-based regulation,
- optimized design and operating practices,
- reduced commissioning costs,
- enhanced personnel safety,
- retained knowledge of most skilled staff,
- automated data interpretation and
- improved work management. (IEEE C57.143)

In this thesis the evaluation is made for the economic benefits only, so the focus is in the first four mentioned benefits. Functional and psychological benefits, such as better company reputation (Grisaru & Friedman 2000), are not covered.

The following equations and Tables describe the value that the online DGA monitor is providing to the customer in direct profits and cost savings. They are based on the statistical failure probabilities and estimations which were presented in the Chapter 4.

Improved Loading Capacity

If the power transformer conditions are closely monitored, the risk can be significantly reduced. This makes it possible to improve the loading capacity of the unit and run it on overload (Sparling). To quantify this benefit, the additional loading margin provided by monitoring needs to be stated.

The rated capacity of a unit is the load level that will result in internal temperature not exceeding the limits set forth by standard producing bodies such as IEEE and IEC. It could be estimated that a power transformer with online DGA monitoring can be loaded with higher loading rate than the units without special monitoring with the same degree of confidence. (IEEE C57.143) The economic value ascribable to overload is obtained by subtracting the aging cause by the normal load from aging caused by the overload. The net loss of transformer life can then be related to the normal life duration and the transformer cost to quantify the value of the loss of transformer life attributable to the overload (IEEE C57.143).

From an economic point of view, it is very attractive to increase the load on a transformer above its rated load capability. Using these simplified assumptions along with steady load and steady ambient temperature, the benefits of online monitoring have been assessed. The transformer overloading benefit without online monitoring can be calculated with the equation 9.

$$B_{O1} = P \cdot t_{ol} \cdot V_D \cdot P_{E1} - \frac{C_{tr} \cdot t_{ol} \cdot (A_1 - 1)}{t_{tr}}, \tag{9}$$

B_{O1}	*Transformer overloading benefit without online monitoring [€/a],*
P	*Nominal power of power transformer,*
C_{tr}	*Replacement cost of transformer,*
t_{ol}	*Duration of overloading,*
V_D	*Value of delivered energy,*
P_{E1}	*Extra loading without monitoring,*
A_1	*Aging acceleration factor at extra load without monitoring,*
t_{tr}	*Transformer normal life duration*. (IEEE C57.143)

The transformer overloading benefit with online DGA monitoring can be calculated with the equation 10.

$$B_{O2} = P \cdot t_{ol} \cdot V_D \cdot P_{E2} - \frac{C_{tr} \cdot t_{ol} \cdot (A_2 - 1)}{t_{tr}}, \tag{10}$$

B_{O2}	*Transformer overloading benefit from online monitoring [€/a],*
P	*Nominal power of power transformer,*
C_{tr}	*Replacement cost of transformer,*
t_{ol}	*Duration of overloading,*
V_D	*Value of delivered energy,*
P_{E2}	*Extra loading with monitoring,*
A_2	*Aging acceleration factor extra load with monitoring,*
t_{tr}	*Transformer normal life duration.* (IEEE C57.143)

The actual value gained from online DGA monitor can be calculated by subtracting B_{O1} from B_{O2}. This is considered as B_O.

IEEE C57.143 claims that it could be estimated that a transformer can be loaded up to 110 % without special monitoring and that online monitoring will allow loads up to 120 % with the same degree of confidence. Some researches say that 120 % should be loaded only for 2 hours maximum and, also, there can be differences between different conditions and outside temperatures (Nuijten & Geschiere 2005). The maximum value in this thesis, 24 hours, presents that the extra loading is run for one day annually. It is known that 110 % loading is in successful use in some companies (Alatalo 2016).

The price level for 100 MVA power transformer is about 1 million euros (Gratschev 2016a) and for 500 MVA unit the normal list price is about 5 million euros (U.S. Department of Energy 2012). In this thesis the 1000 MVA unit is considered to cost 12 million euros, which is in line with the general price level (U.S. Department of Energy 2012).

The value of extra delivered energy is considered to be as much as normal transmitted energy (Ojanen & Mertanen 2016a). The variation for that in Finland has been chancing from 5 €/h to 150 €/h, depending on the season and the time, while current year median value is 29 €/h (Fingrid 2016). However, the price level may vary a lot between countries.

The loss of transformer life can be calculated from the aging acceleration factor (IEEE C57.143), which increases exponentially with the temperature rise caused by the overload. Continuous 110 % loading leads to a hot-spot temperature of 120 °C and an aging acceleration factor of 2.7. For a 120 % loading, the hot-spot temperature is assumed to be a constant 135 °C with an aging acceleration factor of 11. Therefore 100 hours at that temperature is equivalent to 1100 hours at the rated temperature 110 °C.

The transformer normal life duration is a conventional reference for continuous duty under normal ambient temperature and rated operating conditions (IEEE C57.143). In the following calculations, a normal life duration is assumed to be 40 years, which is approximately 350,000 hours.

While assuming that the load and ambient temperature are steady, the following Table 5.1 presents the input and output values for the equation 9.

Table 5.1 Improved Loading Capacity Without Online DGA Monitoring, B_{O1}.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	500 MVA	1,000 MVA
C_{tr}	1,000,000 €	5,000,000 €	12,000,000 €
t_{ol}	1 h	24 h	24 h
V_D	5 €/MWh	29 €/MWh	35 €/MWh
P_{E1}	10%	10%	10%
A_{110}	2.7	2.7	2.7
t_{tr}	350,000 h	350,000 h	350,000 h
TOTAL	**45 €**	**34,217 €**	**82,601 €**

As the Table 5.1 presents, the variables for the improved loading capacity can vary a lot depending on a power transformer and how it is used.

The Table 5.2 presents the improved overloading capacity with online DGA monitoring which allows 120 % loading rate. At the same time the aging acceleration factor increases from 2.7 to 11. All the other variables remain the same. The Table 5.2 presents the input and output values for the equation 10.

Table 5.2 Improved Loading Capacity With Online DGA Monitoring, B_{O2}.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	500 MVA	1,000 MVA
C_{tr}	1,000,000 €	5,000,000 €	12,000,000 €
t_{ol}	1 h	24 h	24 h
V_D	5 €/MWh	29 €/MWh	35 €/MWh
P_{E2}	20%	20%	20%
A_{120}	11.0	11.0	11.0
t_{tr}	350,000 h	350,000 h	350,000 h
TOTAL	**71 €**	**66,171 €**	**159,771 €**

As the Table 5.2 presents, the 120 % loading improves the profitability of the power transformer.

Extended Lifetime

Whenever a transformer in considered for replacement, a comprehensive condition assessment is usually carried out. This would imply a number of electrical and chemical tests, some of them requiring an outage, leading to a diagnostic on the insulation condition. In this context, the economic value of online monitoring is difficult to assess, as the decision must also take into account other considerations such as capital availability, delivery time for new units and the perception that the insulation condition could start to degrade in the near future. Considering the large financial consequence of deferring transformer replacement, it is, however, worthwhile to attempt an evaluation of the economic contribution that could be expected from online DGA monitoring (Sparling).

IEEE C57.143 states that the transformer is normally removed from service if the failure rate is believed to rise beyond the acceptable level. For an aging transformer, the risk is not so much the remaining value of the unit as the inconvenience of an unscheduled outage. At this point the monitoring becomes critical to maintain an acceptable level of reliability. By providing early detection of incipient faults, online monitoring provides visibility of issues earlier, reducing the risk of unexpected failures and unscheduled outages, thus raising the reliability and reducing overall risk. The Figure 5.3 presents the lifetime of a power transformer with and without online DGA monitoring.

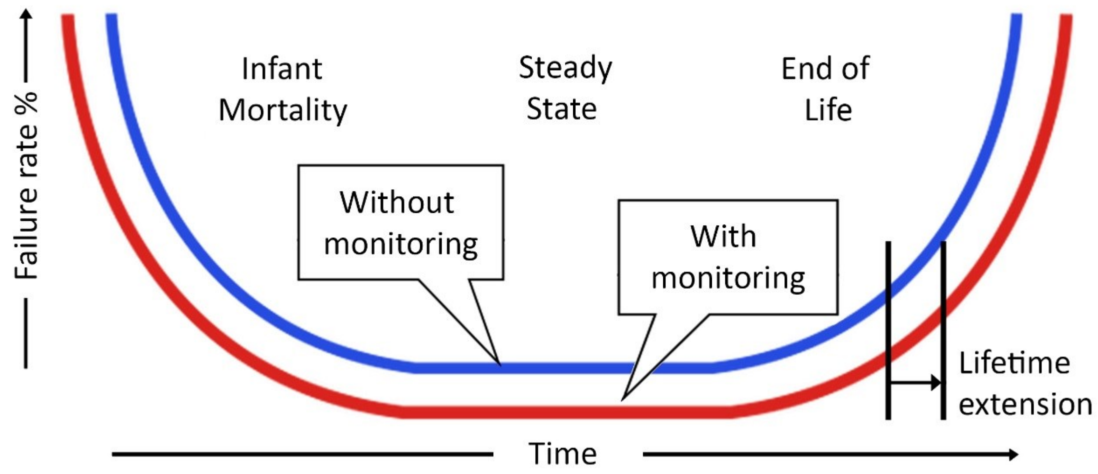

Figure 5.3 The Increased Lifetime of Power Transformer (IEEE C57.143, modified).

The Figure 5.3 shows that the online DGA monitoring re-shapes the ‘bath-tub curve’, which was presented in the sub-chapter 3.2. With monitoring, it is possible to keep the failure rate lower which extends the lifetime of a power transformer. The benefit from deferred replacement is directly proportional to the current interest rate and the capital cost of a new unit (Sparling) and the value of transformer replacement deferral can be calculated with the equation 11.

$$V_R = C_{tr} \cdot I \cdot t_{ext} , \quad (11)$$

V_R	*Transformer replacement deferral value because of online monitoring [€],*
C_{tr}	*Cost of a new power transformer,*
I	*Current interest rate,*
t_{ext}	*Lifetime extension*. (IEEE C57.143)

The benefit from extended lifetime is directly proportional to the current interest rate and the capital cost of a new unit. In this thesis, the annual interest rate is considered to be 3 % (Market Watch 2016). The online DGA monitor allows to move from TBM to CBM and, in practice, this in general means extended lifetime. The Table 5.3 presents the annual value for lifetime extension. The Table presents the input and output values for the equation 11.

Table 5.3 Extended Lifetime, V_R.

Variable	Minimum Value	Normal Value	Maximum Value
C_{tr}	1,000,000 €	5,000,000 €	12,000,000 €
I	3 %/a	3 %/a	3 %/a
t_{ext}	1 a	1 a	1 a
TOTAL	**30,000 €**	**150,000 €**	**360,000 €**

As presented in the Table 5.3, the saved costs from extending the power transformer lifetime can be remarkable depending on the interest rate and the actual price of the power transformer.

Reduced Maintenance Costs

In many cases, additional monitoring can reduce the frequency of manual inspections. Direct time savings are achieved during disassembly, manual inspection, reassembly and reporting. Also, there can be additional savings in travel time and vehicle expenses, depending on the locations of the transformers.

With some large power transformers, it is common to have visits for an overview of the substation. Since there is presently no monitoring system that can completely replace the visual inspection, it is felt that periodic inspections will remain necessary in the foreseeable future and therefore no savings are accounted for that (IEEE C57.143).

A more elaborate inspection, with outage, is carried out typically every 6 years and includes cooling system and protective equipment verification along with a number of electrical tests. It is not clear if monitoring could allow postponing of these activities and therefore no savings are accounted for in the example calculation that follows. (IEEE C57.143)

Instead, the annual benefit of saved maintenance costs can be calculated from the decreased number of site visits and offline oil sampling frequency with the equation 12.

$$B_M = N_{voff} \cdot (C_v + C_{lab}) - N_{von} \cdot C_v, \tag{12}$$

B_M	*Annual preventive maintenance benefit from online monitoring [€/a],*
N_{voff}	*Number of offline oil samples without online DGA monitoring,*
N_{von}	*Number of offline oil samples with online DGA monitoring,*

C_v *Cost of each site visit,*
C_{lab} *Cost of oil analysis in laboratory.*

It can be estimated that each visit to the substation costs about 1,000 € for the company (Ojanen & Mertanen 2016b) so every visit that can be left out, delivers extra value for the monitor. It is a normal practice that the offline oil samplings are taken from one to three times a year and the online DGA monitoring decreases that number by one or two.

Taking a manual offline oil sample usually costs a few hundred euros (Khoshrou 2016) and the actual analysis in oil laboratory then costs usually another few hundred (Nyman 2016; Gratschev 2016b). Sometimes the laboratory can be located even to different country, so some logistic expenses has to be added to total costs as well (Keitoue 2016).

The following Table 5.4 presents the value for reduced maintenance costs. The Table presents the input and output values for the equation 12.

Table 5.4 Reduced Maintenance Costs, B_M.

Variable	Minimum Value	Normal Value	Maximum Value
N_{voff}	1	2	3
N_{von}	0	1	2
C_v	500 €	1,000 €	2,000 €
C_{lab}	200 €	300 €	500 €
TOTAL	**700 €**	**1,600 €**	**3,500 €**

As presented in the Table 5.4, the gained savings from automated oil sampling are valid. The bigger the annual sampling frequency is, the bigger the savings.

Reduced Failure-Related Repair or Replacement Costs

Another recognized benefit (IEEE C57.143) from online DGA monitoring is the savings that can be achieved from repair costs. In this case, the purpose of an online monitor is to convert the major or catastrophic failures to smaller failures that can be repaired at a reduced cost during a planned outage. Therefore the gain from reduction in major faults will be somewhat attenuated by an increase in minor faults or predictive maintenance actions.

The benefit from failure resolution can be calculated by taking into account the repair cost for major failure with and without online monitoring, replacement and collateral damage costs with and without online monitoring and repair cost for early detection of major and catastrophic failures (IEEE C57.143). In this thesis, a multiplier X has been used to reflect that the repair cost for a major failure without advance warning is X times higher than the cost of repairing the unit in reaction to a predictive alarm resulting from early detection. The multiplier Y has been used to reflect the replacement cost and collateral damage resulting from a catastrophic failure.

The annual benefit from reduced failure-related repair or replacement costs can be calculated with the equation 13.

$$B_F = C_{pre} \cdot p_f \cdot p_{nd} \cdot E \cdot (X \cdot p_{noncat} + Y \cdot p_{cat} - 1), \tag{13}$$

B_F	*Reduced failure-related repair or replacement costs [€/a],*
C_{pre}	*Predictive repair costs for system with early detection,*
p_f	*Power transformer failure rate,*
p_{nd}	*Current rate of not detectable failures,*
E	*Expected monitoring system efficiency,*
X	Multiplier for a major failure repair costs,
Y	Multiplier for catastrophic failure repair costs,
p_{noncat}	*Proportion of failures that are non-catastrophic,*
p_{cat}	*Proportion of failures that are catastrophic.* (IEEE C57.143)

To complete the benefit evaluation in regard to failure resolution, values should be assigned to the average repair cost under various scenarios. It should be recognized that the cost for repair when early detection allows predictive repairs, will be lower than the cost associated with repair of units where early detection is not provided. In turn, collateral damage can contribute even more to the total resolution cost. (IEEE C57.143)

The prices of new units is considered to be the same as they were in the earlier Tables 5.1, 5.2 and 5.3. According to Gratschev (2016a), usually 20-40 % of the price of a new power transformer is considered to be the maximum amount for predictive repair costs. After that, companies usually invest in a new unit. Also the age is a big factor and the older the unit, the easier the new investment is made. The current failure rate, rate of not detectable failures, expected monitoring system efficiency, proportion of the catastrophic and non-catastrophic failures are the same than in the Figure 4.6.

The order of magnitude of the difference between these various costs will vary depending on the application. In this thesis, the multiplier of 7.5 is used to reflect that the repair cost for a major failure without advance warning is 7.5 times higher than the cost of repairing the unit in reaction to a predictive alarm resulting an early detection. A multiplier of 25 has been used to reflect the replacement cost and collateral damage resulting from a catastrophic failure. These multipliers are similar than in IEEE C57.143.

The Table 5.5 presents the variables for these savings. The Table presents the input and output values for the equation 13.

Table 5.5 Reduced Failure-Related Repair or Replacement Costs, B_F.

Variable	Minimum Value	Normal Value	Maximum Value
C_{tr}	1,000,000 €	5,000,000 €	12,000,000 €
C_{pre}	20%	20%	20%
p_f	0.53%	0.53%	0.53%
p_{nd}	50%	50%	50%
E	75%	75%	75%
X	7.5	7.5	7.5
Y	25	25	25
p_{noncat}	98.7%	98.7%	98.7%
p_{cat}	1.3%	1.3%	1.3%
TOTAL	**2,674 €**	**13,371 €**	**32,090 €**

As presented in the Table 5.5, some savings can be gained by reducing the failure-related repair or replacement costs.

5.2.2 Total Sacrifises

When purchasing a product or service, there will always be additional costs in over the actual purchasing price. Preparation of bid request, technical evaluation, logistics, documentation and yearly operating costs cause expenses (IEEE C57.143). According to Sparling (2016), installation, communication protocols, alarm handling, information management, IT-services and data storage have a big role when the total cost for the monitor is defined. After the online DGA monitor is taken out from its operation, the disposal may cause some costs. Also, when investing in new devices, change management has to take place. New systems require training on how they work, and, most important, what the information coming out of them means in practice. The costs can be categorized into three types, which were also presented in the sub-chapter 5.2:

- acquisition costs,
- possession costs and
- usage costs. (Hutt & Speh 2013)

According to Hutt & Speh (2013), acquisition costs include the purchase price and logistic costs, but also the costs of evaluating suppliers and correcting possible errors in delivery. Possession costs include financing, inspection, insurances and other internal handling costs. Usage costs are related to installation, employee training and maintenance, as well as product replacement and disposal.

The TCO of online DGA monitor can be calculated with the equation 14.

$$TCO = C_A + C_P + C_U, \tag{14}$$

TCO *Total cost of ownership [€],*
C_A *acquisition costs,*
C_P *possession costs,*
C_U *usage costs*. (Hutt & Speh 2013)

However, significant variability exists in how life cycle costing is carried out in electricity networks. Some companies tend that they do not perform life cycle costing at all, whilst for those that do, the calculation methods varies significantly. For example, some electricity networks businesses do not consider inflation or depreciation rates in their costing, whilst others do. Similarly, not all networks businesses consider the costs of disposal in their life cycle cost calculations. (IEC 2015)

When investing in online DGA monitoring, the first expense is naturally the actual price of the unit itself. Vaisala DGA monitor is considered to cost 40,000 € including delivery (Leivo 2016). Instead, the possession costs depend usually only on customers' own processes and in in this case, the number is minimal because there is no need for storage, inspections or insurances.

According to Ojanen & Mertanen (2016a) the usage costs depend how complex the installation is. Often the online DGA monitor can be installed directly to the power transformer hoses, but in some cases lot of extra work is required especially with oil pipes and couplings (Pyykkö 2015). This may cost basically anything between 1,000 € (Alatalo 2016) and 20,000 € (Ojanen & Mertanen 2016a) depending how much planning, installation work and training needs to be done. The training is considered to cost 2,000 € (Ojanen & Mertanen 2016b).

The disposal of the online DGA monitor also costs money. There is no actual residual value for the unit, but uninstalling and the disposal is considered to cost 1,000 € (Ojanen & Mertanen 2016a).

The Table 5.6 presents the TCO for the online DGA monitor. The Table presents the input and output values for the equation 14.

Table 5.6 TCO of the Online DGA Monitor.

Variable	Minimum Value	Normal Value	Maximum Value
C_A	40,000 €	40,000 €	40,000 €
C_P	0 €	0 €	0 €
C_U	3,000 €	5,000 €	24,000 €
TOTAL	**43,000 €**	**45,000 €**	**64,000 €**

As presented in the Table 5.6, the biggest cost for online DGA monitor is the actual purchase price. Some costs come also from installation and employee trainings, but they can be considered as minor costs.

5.3 Total Cost of a Failed Power Transformer

When the power transformer fails, the costs will always be high. There is no single answer to describe the sum, because it depends on so many factors. The cost of an unexpected failure can be multiple times the cost of the actual power transformer (Agoris et al. 2005). However, although the total cost is different, there are lots of common factors with the failures. The costs can be divided into direct and indirect costs (Bartley 2003).

Direct Costs

After a failure there will be costs which are directly related to reinstating the power transformer to use. That is usually done by one of the following methods, which all cause different costs:

- disposal of the old power transformer and invest in a new one,
- repairing the power transformer on factory or
- repairing the power transformer on-site. (CIGRE TB 422 2010)

All of these methods cause some downtime for a power transformer.

If the power transformer cannot be repaired, it has to be renewed completely. This means the disposal of the old unit and investing in a new one. Also, in some cases, it is possible that the old transformer has some amount of disposal value on, for example, copper or iron (Boss et al. 2002; Gratschev 2016a). Sometimes it is possible to install a backup transformer before the new unit is purchased, which lowers the downtime.

Planning the logistics and transportation for new power transformer is often really complex. Planning heavy lift transportation on public roads, rail-roads or sea-ways requires work to identify a suitable route. The power transformers should always be moved by the standard IEEE C57.150.

The long transport distances, limitations and costs are the reason for on-site repair instead of the factory. The distances between the substations and factory type or repair shop can be thousands of kilometers (Elovaara et al. 1994). With the on-site repair, the most critical equipment, such as cranes, winding machines, core stacking table, drying and testing equipment has to be available as fast as possible to minimize the power transformer downtime.

The price for a new power transformer is considered to be the same as it was presented in the Table 5.1 earlier. The planning and installation costs usually about 40,000 €.

(Ojanen & Mertanen 2016b) Also the age is a big factor and the older the unit, the easier the new investment is made. (Gratschev 2016a)

The costs for transportation and logistics can be anything up to 50 % of the total costs of the new power transformer or factory repaired transformer (CIGRE TB 445 2011) including the disposal of the old unit. Even in Finland, where the distances are relatively short, the logistic costs to the factory can be over 100,000 € for the big units including cranes and carriages. For the small units, the costs are usually 30,000 € minimum. (Gratschev 2016b)

The Table 5.7 presents the costs for the new power transformer investment.

Table 5.7 Disposal of the Old Power Transformer and Investing in a New One.

Variable	Minimum Value	Normal Value	Maximum Value
C_{tr}	1,000,000 €	5,000,000 €	12,000,000 €
C_{plan}	40,000 €	40,000 €	40,000 €
C_{log}	100,000 €	1,250,000 €	6,000,000 €
TOTAL	**1,140,000 €**	**6,290,000 €**	**18,040,000 €**

As presented in the Table 5.6, the renewal of a power transformer is expensive. Even the logistic costs alone can increase to millions of euros and, also, the general planning costs are usually tens of thousands euros as overheads.

It is not always necessary to invest in a new power transformer. The unit can be also transported to the factory and do the maintenance and repair activities there. As in the previous case, also this causes costs from general planning, logistics and repair work.

These are presented in the Table 5.8. The repairing costs are considered to be 20 % of the price of the new unit.

Table 5.8 Repairing the Power Transformer on Factory.

Variable	Minimum Value	Normal Value	Maximum Value
C_{plan}	40,000 €	40,000 €	40,000 €
C_{log}	30,000 €	50,000 €	100,000 €
C_{rep}	200,000 €	1,000,000 €	2,400,000 €
TOTAL	**270,000 €**	**1,090,000 €**	**2,540,000 €**

As presented in the Table 5.8, the repairing at a factory is much cheaper than the renewal. The overheads from planning stay at the similar level compared to the renewal, but the logistic costs usually decrease a lot.

The long transport distances, limitations and costs are the reason for on-site repair. The distances between the substations and factory type of repair shop can be thousands of kilometers (Elovaara et al. 1994). It is estimated that the total cost of on-site repair is only 10 – 15 % of the cost of the same repair in a factory or a repair shop (Sobocki et al. 2002). However, even with the on-site repair, the most critical equipment, such as cranes, winding machines, core stacking table, drying and testing equipment has to be available as fast as possible (CIGRE TB 445 2011) to minimize the power transformer downtime.

Table 5.9 Repairing the Power Transformer On-Site.

Variable	Minimum Value	Normal Value	Maximum Value
C_{plan}	4,000 €	4,000 €	6,000 €
C_{log}	3,000 €	5,000 €	15,000 €
C_{rep}	20,000 €	100,000 €	360,000 €
TOTAL	**27,000 €**	**109,000 €**	**381,000 €**

As presented in the Table 5.9, the planning overheads and logistic costs are a lot smaller when the repair is done on-site. Also the repairing costs decrease significantly compared to factory repair.

Indirect Costs

Indirect costs can also be fixed or variable and they can be traced to a product or customer (Hutt & Speh 2013). Also the general overheads and activities such as administrative costs can be seen as costs caused by the failure. So, indirect costs are related to the power transformer failure but they are caused by something else than the actual repair work. The most important ones can be listed as:

- cost of power not generated,
- cost of contractual power not delivered,
- cost of lost production in an industrial plant and
- consequential costs from damages, liability costs and customer compensation. (CIGRE TB 422 2010)

This thesis focuses only on these costs. However, environmental and social impacts are also a big part of a failure. However, it is difficult to describe them with monetary terms without further knowledge about the case. Some of them can be listed as:

- personal injuries,
- pollution to air and soil,
- social aspects of the customer,
- damages of the property and
- public image of the company. (CIGRE TB 422 2010)

The following sub-chapter 5.3.1 goes through the failure cost types more deeply while the sub-chapter 5.3.2 discusses about the N-1 criterion.

5.3.1 Failure Cost Types

Several different kinds of indirect costs are related to power transformer failures. The following equations describe the value that the online DGA monitor is providing to the customer in indirect cost savings. They are based on the statistical failure probabilities and estimations which were presented in the Chapter 4.

Cost of Power Not Generated

Failure of a GSU transformer can have major economic impacts when the loss of a transformer leads to generation deficit and purchase of replacement power. The cost of power not generated, without online monitoring, can be calculated with the equation 15.

$$C_{ng1} = P \cdot p_f \cdot p_{nd} \cdot f_{load} \cdot t_{outage} \cdot C_R, \tag{15}$$

C_{ng1} *Cost of power not generated without online monitoring [€/a],*
P *Nominal power of power transformer,*
p_f *Power transformer failure rate,*
p_{nd} *Current rate of not detectable failures,*
f_{load} *Power transformer load rate,*
t_{outage} *Duration of outage,*
C_R *Cost of replacement energy.* (IEEE C57.143)

The cost of power not generated, with online monitoring, can be calculated with the equation 16.

$$C_{ng2} = P \cdot p_f \cdot p_{nd} \cdot (1 - E) \cdot f_{load} \cdot t_{outage} \cdot C_R, \tag{16}$$

C_{ng2} *Cost of power not generated with online monitoring [€/a],*
P *Nominal power of power transformer,*
p_f *Power transformer failure rate,*
p_{nd} *Current rate of not detectable failures,*
E *Expected monitoring system efficiency,*
f_{load} *Power transformer load rate,*
t_{outage} *Duration of outage,*
C_R *Cost of replacement energy.* (IEEE C57.143)

The actual value gained from online DGA monitor can be calculated by subtracting C_{ng2} from C_{ng1}. This is considered as C_{ng}.

During the power transformer failure it is naturally not possible to generate power. However, if the power station is in important role, such as a nuclear power plant, it is necessary to purchase the lost power from somewhere else. Because of the big nominal power of nuclear plant reactors, the cost of power not generated is usually really big. The nominal power can be 1,500 MVA and the loading rate is usually stable 90 % or even 95 % (Härmälä et al. 2016).

The failure rate for GSU power transformer is taken from the Table 4.3 and the rate of not detectable failures are from the Figure 4.6. In case of an unexpected failure, the spare transformer can be installed usually in 1 or 2 weeks (Gratschev 2016b). However, in some cases, it may take even 11 to 14 weeks. If the spare transformer is not available, it may take several months or even years before the new unit is on duty. (Alfonso 2016)

The cost of power not generated is calculated from cost of replacement energy. This price is considered to be the same as it was with extra delivered energy, 29 €/MWh. The Table 5.10 presents the situation. The Table presents the input and output values for the equation 15.

Table 5.10 Cost of the Power Not Generated Without Online DGA Monitoring, C_{ng1}.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	500 MVA	1,000 MVA
p_f	0.95%	0.95%	0.95%
p_{nd}	50%	50%	50%
f_{load}	90%	95%	95%
t_{outage}	7 d	14 d	98 d
C_R	5 €/MWh	29 €/MWh	35 €/MWh
TOTAL	**359 €**	**21,985 €**	**371,469 €**

As presented in the Table 5.10, the cost of power not generated may be very expensive to the power plant.

If the online DGA monitor has given a signal of a failure in advance, the time can be reduced to a few days or one week with round-the-clock work (Gratschev 2016b). However, if the spare transformer is not available anywhere near, the outage can last as long as it takes without the online DGA monitor. Other values remain the same as they were in previous situation.

The Table 5.11 presents the input and output values for the equation 16.

Table 5.11 Cost of the Power Not Generated With Online DGA Monitoring, C_{ng2}.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	500 MVA	1,000 MVA
p_f	0.95%	0.95%	0.95%
p_{nd}	50%	50%	50%
E	75%	75%	75%
f_{load}	90%	95%	95%
t_{outage}	3 d	7 d	98 d
C_R	5 €/MWh	29 €/MWh	35 €/MWh
TOTAL	**38 €**	**2,748 €**	**92,867 €**

As presented in the Table 5.11, the online DGA monitor lowers the probability of a failure, and reduces the outage period. This creates savings compared to the situation without online monitoring.

Cost of Contractual Power Not Delivered

Each customer type has varying demand for the continuity of electricity. The cost of interruption is dependent on many customer characteristics, such as hour of the day, season of the year, heating solutions and geographical location (Palola 2014).

An important issue here is the so called N-1 criterion in the design of the power grids. N-1 is covered in the sub-chapter 5.3.2 which gives more the specific equations for the cost of contractual power not delivered. The basic situations (N-0 criterion), where the cost of contractual power not delivered, without online monitoring and with N-0 criterion, can be calculated with the equation 17.

$$C_{nd1(N-0)} = P \cdot p_f \cdot p_{nd} \cdot f_{load} \cdot t_{outage} \cdot V_{nd} \,, \qquad (17)$$

$C_{nd1(N\text{-}0)}$	*Cost of contractual power not delivered [€/a],*
P	*Nominal power of power transformer,*
p_f	*Power transformer failure rate,*
p_{nd}	*Current rate of not detectable failures,*
f_{load}	*Power transformer load rate,*
t_{outage}	*Duration of outage,*
V_{nd}	*Value of energy not delivered.* (IEEE C57.143)

The cost of contractual power not delivered, with online monitoring and with N-0 criterion, can be calculated with the equation 18.

$$C_{nd2(N-0)} = P \cdot p_f \cdot p_{nd} \cdot (1 - E) \cdot f_{load} \cdot t_{outage} \cdot V_{nd}\ , \tag{18}$$

$C_{nd2(N\text{-}0)}$	*Cost of contractual power not delivered [€/a],*
P	*Nominal power of power transformer,*
p_f	*Power transformer failure rate,*
p_{nd}	*Current rate of not detectable failures,*
E	*Expected monitoring system efficiency,*
f_{load}	*Power transformer load rate,*
t_{outage}	*Duration of outage,*
V_{nd}	*Value of energy not delivered.* (IEEE C57.143)

The actual value gained from online DGA monitor can be calculated by subtracting $C_{nd2(N\text{-}0)}$ from $C_{nd1(N\text{-}0)}$. This is considered as $C_{nd(N\text{-}0)}$.

TSOs and DSOs are required to deliver the power to customers they have contracts with. In case of a power transformer failure, the transmission or distribution is interrupted if the N-0 criterion is in use. While calculating the costs for this, multiple variables has to be known.

The used power, the failure rate, rate of not detectable failures and failure duration are in important role (IEEE C57.143) while estimating the interruption costs. The used values for these variables are the same that were used in earlier cases in this thesis. The loading rate for normal TSO and DSO power transformers is usually only 40-50 % from the nominal power (Ojanen & Mertanen 2016a).

The value of not delivered energy is considered to be the same as it was with extra delivered energy and not generated power. The Table 5.12 presents the cost of contractual power not delivered without online DGA monitoring with N-0. It presents the input and output values for the equation 17. The normal value is for the nominal power of 100 MVA because these are typically DSO power transformers, which are usually smaller than the GSU or TSO units.

Table 5.12 Cost of the Contractual Power Not Delivered Without Online DGA Monitoring, N-0, $C_{nd1(N\text{-}0)}$.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	100 MVA	1,000 MVA
p_f	0.53%	0.53%	0.53%
p_{nd}	50%	50%	50%
f_{load}	40%	50%	90%
t_{outage}	7 d	14 d	98 d
V_{nd}	5 €/MWh	29 €/MWh	35 €/MWh
TOTAL	**89 €**	**1,291 €**	**196,333 €**

As presented in the Table 5.12, the not delivered power with N-0 criterion is costing money.

The following Table 5.13 presents the cost of contractual power not delivered with online DGA monitoring with N-0 criterion. The expected monitoring system efficiency is the same than in the earlier sub-chapters. The Table presents the input and output values for the equation 18. Also in this Table, the nominal power of the normal value is 100 MVA.

Table 5.13 Cost of the Contractual Power Not Delivered With Online DGA Monitoring, N-0, $C_{nd2(N\text{-}0)}$.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	100 MVA	1,000 MVA
p_f	0.53%	0.53%	0.53%
p_{nd}	50%	50%	50%
E	75%	75%	75%
f_{load}	40%	50%	60%
t_{outage}	3 d	7 d	98 d
V_{nd}	5 €/MWh	29 €/MWh	35 €/MWh
TOTAL	**10 €**	**161 €**	**32,722 €**

As presented in the Table 5.13, the online DGA monitoring has a huge effect on the costs of not delivered power.

Cost of Lost Production in an Industrial Plant

In most of the industrial plants, the production depends on some critical industrial transformer. These transformers are usually custom designed for the particular plant and provide power to the process. The lack of power may stop the whole industrial plant and when the power transformer is out of service, the whole production of the plant is lost until a failed unit gets replaced or fixed.

The cost of lost production in an industrial plant, without online monitoring, can be calculated with the equation 19.

$$C_{tlp1} = p_f \cdot p_{nd} \cdot t_{outage} \cdot C_{lp} , \tag{19}$$

C_{tlp1} *Total cost for loss of production [€/a],*
p_f *Power transformer failure rate,*
p_{nd} *Current rate of not detectable failures,*
t_{outage} *Duration of outage,*
C_{lp} *Cost of loss of production*. (IEEE C57.143)

The cost of lost production in an industrial plant, with online monitoring, can be calculated with the equation 20.

$$C_{tlp2} = p_f \cdot p_{nd} \cdot (1 - E) \cdot t_{outage} \cdot C_{lp} \,, \tag{20}$$

C_{tlp2}	*Total cost for loss of production [€/a],*
p_f	*Power transformer failure rate,*
p_{nd}	*Current rate of not detectable failures,*
E	*Expected monitoring system efficiency,*
t_{outage}	*Duration of outage,*
C_{lp}	*Cost of loss of production.* (IEEE C57.143)

The actual value gained from online DGA monitor can be calculated by subtracting C_{tlp2} from C_{tlp1}. This is considered as C_{tlp}.

The power variation in industrial plant can be 1.5-160 MVA while the loading rate is anything between 10 % and 110 % (Alatalo 2016). The costs for the lost production can be from thousands to millions of euros in a day (Ojanen & Mertanen 2016b) depending on the factory. The production is lost but still all the employees has to get paid and also other fixed costs are running all the time. (Gratschev 2016b) The cost is not calculated from the lost revenue but the actual lost profit. The production stop may last for 4 hours if the spare transformer is available, and if not, the delay can more than a year (Alatalo 2016).

The outage duration depends not only the availability of the spare transformer, but also the capability to start up the production again. It is possible that the production has to be started in several parts so the production outage can last from a few hours to years. (Alatalo 2016) This case without online DGA monitoring is presented in the Table 5.14 which describes the input and output values for the equation 19.

Table 5.14 Cost of the Lost Production in an Industrial Plant Without Online DGA Monitoring, C_{tlp1}.

Variable	Minimum Value	Normal Value	Maximum Value
p_f	0.53%	0.95%	0.53%
p_{nd}	50%	50%	50%
t_{outage}	7 d	14 d	365 d
C_{lp}	20,000 €/d	500,000 €/d	2,000,000 €/d
TOTAL	**371 €**	**33,250 €**	**1,934,500 €**

As presented in the Table 5.14, the power of the transformer do not have any effect on cost of lost production. The costs come from lost revenues and other fixed costs.

The similar situation with online DGA monitor is presented in the Table 5.15 which presents the input and output values for the equation 20.

Table 5.15 Cost of the Lost Production in an Industrial Plant With online DGA Monitoring, C_{tlp2}.

Variable	Minimum Value	Normal Value	Maximum Value
p_f	0.53%	0.95%	0.53%
p_{nd}	50%	50%	50%
E	75%	75%	75%
t_{outage}	7 d	14 d	365 d
C_{lp}	20,000 €/d	500,000 €/d	2,000,000 €/d
TOTAL	**93 €**	**8,313 €**	**483,625 €**

As presented in the Table 5.15, the online DGA monitor improves the situation a lot by lowering the failure rate.

5.3.2 N-1 Criterion

The N-1 criterion means for each network that it is able to withstand the sudden outage of a failed network component at any time without an interruption of supply to any customer (Jongen et al. 2007; Elovaara & Haarla 2011a). In practice, the N-1 reliability is reached when the grids are built as circles or loops. This improves the system security of the supply when the electricity has multiple ways to forward. This means that there is always a parallel transmission path if one grid component fails (Elovaara & Haarla 2011a).

Transmission grids are in practice always designed and with for N-1 reliability (IEC 2015). In some cases DSOs design their grids for N-1, but the general method for them is so called N-0 (Elovaara & Haarla 2011a), meaning any failure will cause an outage and supply interruption (IEC 2015). Also power generation and industrial power transformers are usually N-0 (Gratschev 2016b).

After the N-1 reliable power transformer fails, the network will then be operating in a degraded condition and might not be able to sustain a second incident without interruption to the end user leading in some cases to penalties for unfulfilled contracts (Sparling), which was covered in the sub-chapter 5.4.1. Outages may also occur when the power transformer is taken out of service for maintenance and second minor failure happen during that time (Gratschev 2016b).

There are some costs associated with the operation of a degraded system and with N-1 philosophy. The cost of risk associated with a second failure is the product of the probability of a second failure occurring during the transformer outage, multiplied by the economic consequence of that event. The second failure might occur as a result of a minor failure on the backup transformer or on any associated equipment that would prevent the backup transformer from carrying its duty. (IEEE C57.143)

When the N-1 is taken under consideration, the already presented equations 17 and 18 get the new form, which are presented below. The cost of contractual power not delivered, without online monitoring and with N-1 philosophy, can be calculated with the equation 21.

$$C_{nd1(N-1)} = P \cdot p_f \cdot p_{nd} \cdot f_{load} \cdot \frac{t_{outage}}{t_{year}} \cdot p_{f2} \cdot t_{outage} \cdot V_{nd}, \tag{21}$$

$C_{nd1(N-1)}$	*Cost of contractual power not delivered [€/a],*
P	*Nominal power of power transformer,*
p_f	*Power transformer failure rate,*
p_{nd}	*Current rate of not detectable failures,*
f_{load}	*Power transformer load rate,*
t_{outage}	*Duration of outage on main transformer,*
t_{year}	*Duration of a year in days,*
p_{f2}	*Probability of minor failure on backup transformer,*
$t_{outage2}$	*Duration of minor failure on backup transformer,*
V_{nd}	*Value of energy not delivered.* (IEEE C57.143)

The cost of contractual power not delivered, with online monitoring and with N-1 philosophy, can be calculated with the equation 22.

$$C_{nd2(N-1)} = P \cdot p_f \cdot p_{nd} \cdot (1-E) \cdot f_{load} \cdot \frac{t_{outage}}{t_{year}} \cdot p_{f2} \cdot t_{outage} \cdot V_{nd}, \tag{22}$$

$C_{nd2(N-1)}$	*Cost of contractual power not delivered [€/a],*
P	*Nominal power of power transformer,*
p_f	*Power transformer failure rate,*
p_{nd}	*Current rate of not detectable failures,*
E	*Expected monitoring system efficiency,*
f_{load}	*Power transformer load rate,*
t_{outage}	*Duration of outage main transformer,*
t_{year}	*Duration of a year in days,*
p_{f2}	*Probability of minor failure on backup transformer,*
$t_{outage2}$	*Duration of minor failure on backup transformer,*
V_{nd}	*Value of energy not delivered.* (IEEE C57.143)

The actual value gained from online DGA monitor can be calculated by subtracting $C_{nd2(N-1)}$ from $C_{nd1(N-1)}$. This is considered as $C_{nd(N-1)}$.

In case of the N-1 criterion, the probability of a second, minor, failure is considered to be a magnitude higher than the major failure rate. This outage duration is usually much shorter compared to the major failure, and the normal duration for it is from a few hours to a few days (IEEE C57.143). This is presented in the Table 5.16 as it presents the input and output values for the equation 21.

Table 5.16 Cost of the Contractual Power Not Delivered Without Online DGA Monitoring, N-1, $C_{nd1(N-1)}$.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	500 MVA	1,000 MVA
p_f	0.53%	0.53%	0.53%
p_{nd}	50%	50%	50%
f_{load}	40%	50%	60%
t_{outage}	7 d	14 d	98 d
t_{year}	365 d	365 d	365 d
p_{f2}	5.30%	5.30%	5.30%
$t_{outage2}$	1 h	24 h	7 d
V_{nd}	5 €/MWh	29 €/MWh	35 €/MWh
TOTAL	**0.01 €**	**22.50 €**	**3,192.97 €**

As presented in the Table 5.16, the N-1 criterion decreases the costs remarkably compared to N-0 situation.

The Table 5.17 presents the same situation but with online DGA monitoring. It presents the input and output values for the equation 22.

Table 5.17 Cost of the Contractual Power Not Delivered With Online DGA Monitoring, N-1, $C_{nd2(N-1)}$.

Variable	Minimum Value	Normal Value	Maximum Value
P	100 MVA	500 MVA	1,000 MVA
p_f	0.53%	0.53%	0.53%
p_{nd}	50%	50%	50%
E	75%	75%	75%
f_{load}	40%	50%	90%
t_{outage}	3 d	7 d	98 d
t_{year}	365 d	365 d	365 d
p_{f2}	5.30%	5.30%	5.30%
$t_{outage2}$	1 h	24 h	7 d
V_{nd}	5 €/MWh	29 €/MWh	35 €/MWh
TOTAL	**0.00 €**	**3 €**	**1,197 €**

As presented in the Table 5.17, the online DGA monitor, again, decreases the costs. However, the gained benefits are so small that they can be considered to be zero. The benefits are valid only with extremely high power transformers and long outage times.

5.3.3 Consequential Cost of Catastrophic Power Transformer Failure

In case of catastrophic failure, the indirect costs can increase even more than just presented. If there is fire and the lines fall down, the consequences can be anything up to millions of euros (Ojanen & Mertanen 2016b). The costs may be due to, for example, damages to further components, liabilities to third parties and customer compensation and sanctions from the regulator. There are endless number of variables and factors.

These costs can be much bigger than all the other costs together. The history knows a case where these consequential indirect costs were 77 million euros in total (Bartley 2003).

5.4 The Role of Insurance Companies

Insurances are an important thing for power transformer owners because, in the case of a failure, it is good to have a shared risk to minimize the costs. In practice, insurances are usually taken by all operators in the business (CIGRE TB 248 2004). Usually there is no separate power transformer insurances but, instead, the system is seen as a whole which can then be covered (Sparling 2016). From insurance company perspective, the power transformer is just part of, for example, a production line (Ruohomäki & Särkkä 2016).

There is no fundamental differences between the pricing of the insurances for different transformer types. However, since all the cases are considered individually and risks are different depending on several aspects, it cannot be said that the two similar power transformers in different locations would always have same insurance price. According to Boman (2016), the insurance company will normally identify equipment with high failure rates, generic maintenance issues, and the potential for a catastrophic failure. Insurance companies expect their customers to perform industrial maintenance performances. If one company is doing maintenance really well and another company is not, the risk is higher and insurance is usually more expensive.

It is usually possible to insure the assets from many kind of events. However, Ruohomäki & Särkkä (2016) state that none of the insurances covers the long-term pollution or if the maintenance required by the OEM has not been done. Also, it is normal for old transformer to fail because they are in the end of their normal lifetime.

The insurance types can be divided into three categories:

- property insurance,
- business interruption insurance and
- liability insurance. (Ruohomäki & Särkkä 2016; Boman 2016)

The property insurance is considered as a basic choice. It covers the direct damages to transformer, its surroundings and soil. The value of a power transformer can be considered, for example, that it is 100 % of the replacement value for the first 15 years and, after that, so called "today's value" is calculated. (Ruohomäki & Särkkä 2016)

The business interruption insurance covers the lost production profits if there is downtime in power generation, transmission, distribution or production. If the company is required to supply energy, the insurance covers the extra price when it is bought from other suppliers (Ruohomäki & Särkkä 2016). The idea of the lost production insurance is visualized in the Figure 5.4.

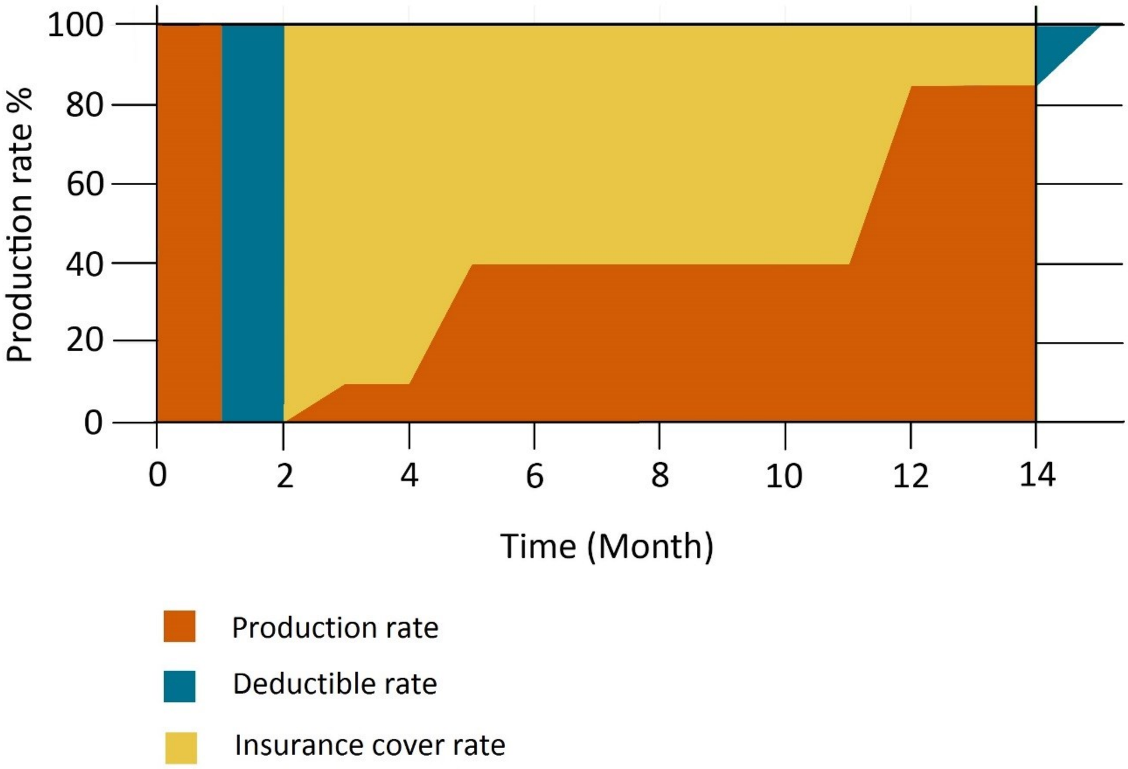

Figure 5.4 The Business Interruption Insurance.

As seen in the Figure 5.4 the lost production insurance covers the lost profit from the factory. In this Figure, the production works normally until the month 1, where the transformer fails and the production rate drops to zero. After that, there is a one month deductible in a lost production. In the following 12 months, the production is started in sections, and after one year the production rate has increased 85 %. After the insurance period is over, the last month is covered without the insurance, so it is considered to be deductible as well. The deductible is covered later in this sub-chapter.

The liability insurance covers the rapidly evolving accidents, such as unexpected accidents or the sanctions caused by suddenly increased pollution levels (Ruohomäki & Särkkä 2016).

The total cost of the insurances can be presented with the equation 23.

$$C_i = C_{ipro} + C_{ibus} + C_{ilia} \ , \tag{23}$$

C_i *Total cost of insurances [€],*
C_{ipro} *Cost of property insurance,*
C_{ibus} *Cost of business interruption insurance,*
C_{ilia} *Cost of liability insurance.*

In case of a failure, the company has to pay the deductible. The deductible is determined by the price level and the companies risk taking willingness, and with bigger price premium it is possible to have a smaller deductible (Boman 2016).

In property and liability insurances, the deductible is defined in euros, while in business interruption insurance, the deductible is defined in weeks or months (Ruohomäki & Särkkä 2016). When there is a business interruption, one week may cause thousand or even millions of euros in lost profits, depending on a company. In case the interruption last for months or years, it will cause huge costs to the insurance company as well.

The deductibles can be presented with the equation 24.

$$D_i = D_{ipro} + D_{ibus} + D_{ilia} \ , \tag{24}$$

D_i *Total deductible of insurances,*
D_{ipro} *Deductible of property insurance,*
D_{ibus} *Deductible of business interruption insurance,*
D_{ilia} *Deductible of liability insurance.*

Because the insurance companies do not insure just a single transformer, there is no actual list price for it. But, if 100,000,000 € factory with 1,000,000 € transformer is fully insured, the annual price for the whole factory is around 100,000 € and 1,000,000 € (Ruohomäki & Särkkä 2016). The exact amount depends on a total risk assumption which variables are at least history information of the company, location, price, occupancy and criticality not just the power transformer but the whole system (Boman 2016). However, it can be said that the power transformer insurance costs are some of thousands of euros annually.

Boman (2016) and Ruohomäki & Särkkä (2016) state that online monitoring can increase the reliability but will normally have a small impact on the insurance price. The deductible for property insurance is defined in euros and for big companies it is usually hundreds of thousands or millions depending on a system. The deductible for business interruptions is usually defined in weeks or months. Also there is usually a maximum time period for compensation, which is considered to be 12 months in this thesis. The liability deductible is defined usually in euros and it considered a lot lower than in property insurance.

The Table 5.18 presents the insurance costs scaled for one power transformer which presents the input and output values for the equation 23.

Table 5.18 Insurance Prices for Power Transformers.

Variable	Minimum Value	Normal Value	Maximum Value
C_{ipro}	1,000 €	5,000 €	10,000 €
C_{ibus}	500 €	2,500 €	5,000 €
C_{ilia}	100 €	500 €	1,000 €
TOTAL	**1,600 €**	**8,000 €**	**16,000 €**

As presented in the Table 5.18, the insurance costs are relatively low for one power transformer compared to the price of the power transformer or online DGA monitor.

The Table 5.19 describes the deductibles in case of a power transformer failure which describes the input values for the equation 24.

Table 5.19 Insurance Deductibles.

Variable	Minimum Value	Normal Value	Maximum Value
D_{ipro}	100,000 €	500,000 €	2,000,000 €
D_{ibus}	2 weeks	1 m	6 m
D_{ilia}	10,000 €	50,000 €	200,000 €

As presented in the Table 5.19, the deductibles are usually much greater than the actual insurance prices. The most remarkable ones are the business interruption deductible of 1 month and the deductible of hundreds of thousands in property insurance.

Anyway, it is crucial to understand that although the insurances cover a lot of costs, the failures always cause extra work and effort to the company which cannot be covered by insurances (Gratschev 2016b).

6. ECONOMIC REVIEW

As presented in the Chapter 5, there are both costs and benefits when investing in online DGA monitor. When designing the condition monitoring system for a power transformer, there are usually several possibilities available, which all are technically capable. In these situations, the best solution is selected by making financial calculations. The calculations are based on the statistical failure probabilities and estimations which were presented in the Chapter 4 and the equations and calculation presented in the Chapter 5 and they may vary significantly from one customer to another

More than one situation described in the Chapter 5 can apply to a given transformer. To determine the total customer value of a monitoring system, it is necessary to add all the benefits together and subtract the costs and compare it to the situation without the online DGA monitor.

6.1 Accounting Methods

There are several methods to study the profitability of the investment (Suomala et al. 2011). In this thesis the *net present value* (NPV) method, *internal rate of return* (IRR) and payback period are presented, and the IRR and payback period method used for actual calculations. All of these methods require some input values from the Chapter 5.

In the calculations, the basic investment is scheduled to the beginning of the online DGA monitor lifetime. It includes the acquisition costs, possession costs and usage costs excluding the disposal value of the unit. The investment period is considered same as the actual physical lifetime of the DGA monitor, since it is not necessary to replace it before it breaks.

Net incomes are the consequence of the investment (Suomala et al. 2011) and they are considered as the difference between the investment costs and the gained cost savings from the DGA. It is assumed that the incomes are scheduled to the end of the year. This can also be used as a minimum requirement for rate of return for the investment. Choosing the interest rate when calculating long-term expenditures is essential, because it defines the time value of money.

Net Present Value

NPV calculations require the prior determination of appropriate interest rate (Discount Rate) as well as the expected lifetime of the DGA unit. NPV should model all the associated costs, including the capitalized costs of losses. (CIGRE TB 248 2004) NPV is calculated by reducing the discounted net incomes and the disposal value from the basic investment. If the NPV is positive, the investment is considered to be profitable. (Suomala et al. 2011) This can be calculated with the equation 25.

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \ , \tag{25}$$

NPV	*Net present value [€]*
t	*Number the year,*
N	*The investment period,*
I	*The discount rate,*
R_t	*The net cash flow.*

Internal Rate of Return

According to Suomala et al. (2011), the IRR is considered as the rate of interest which the cash flow NPV is zero. The investment is profitable if the IRR is greater than the required interest rate of the customer company. The greater the IRR is, the more profitable the investment is.

The equation for the IRR is similar than for NPV and the equation 25. However, now the variable is the interest rate *i* and not the cash flow, which is zero. There is no simple equation for the IRR, but the equation 26 presents the situation.

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+IRR)^t} = 0 \ , \tag{26}$$

NPV	*Net present value,*
t	*Number the year,*
N	*The investment period,*
IRR	*Internal rate of return [%],*
R_t	*The net cash flow.*

The following equation 27 presents the numerical iteration solution for the equation 26.

$$IRR_{n+1} = IRR_n - NPV_n \cdot \left(\frac{IRR_n - IRR_{n-1}}{NPV_n - NPV_{n-1}}\right) \tag{27}$$

IRR_{n+1}	*The n+1:th approximation of the IRR,*
IRR_n	*The n:th approximation of the IRR,*
IRR_{n-1}	*The n-1:th approximation of the IRR.*

In practice, however, the IRR is usually calculated with Microsoft Excel or other similar programs.

Payback Period

The payback period is considered to be the time in which the gained benefits and net incomes are greater than the actual investment. This method does not consider the time-value of the money (Suomala et al. 2011), but since the payback periods are generally short, it does not cause uncertainty to the results.

This method is not suitable for analyzing the profitability of the investment, because it does not take into account the net incomes after the payback period (Suomala et al. 2011). However, with the payback period, it is easily possible to recognize the unfavorable investments by their financial impacts and risk levels.

The payback period $[a]$ can be calculated with the equation 28.

$$Payback\ Period = \frac{Basic\ Investment}{Annual\ Net\ Income}. \tag{28}$$

6.2 Valid Value Propositions

From the total benefits and sacrifices presented in the Chapter 5, not all are valid for value-selling. Improved loading capacity is not something that can be encouraged to do, because it should be used only in extreme situations. Also, it would mean that the power transformer owner is already measured its power transformers wrong and for too low power. Also it can be argued that is the lifetime extension a valid sales argument and benefit or not. The problem is, that it is not known that how long lifetime extension the online DGA monitor truly gives, or does it do that at all. Even if it does, it is not sure that the budgeted capital would not be invested in something else. Therefore, it is not guaranteed that it actually gives any benefits.

The direct costs of a failed power transformer cannot be decreased with the DGA. If the failure happens, the monitoring does not lower the costs. Instead, reduced maintenance costs and reduced failure-related repair or replacement costs can be seen as a valid value proposition and sales argument for all the power transformers. It can be confirmed that the companies actually gain benefit and value from automated monitoring, and also the decreased repair costs are scaled to the DGA unit level. These benefits realize always with all the customers and they happen annually through the whole lifetime of an online DGA unit.

More value is provided through the decreased costs in not generated power, not delivered contractual power and lost production. These are also valid sales arguments, but they can be directed only to the specific customer types. They are, respectively, GSU transformers, TSO and DSO transformers and industrial power transformers. Usually these benefits realize either never or only once, and after that the power transformer is repaired or replaced.

Another thing that is sure for all the online DGA monitor customers, is the total cost of the actual online DGA monitor. Acquisition costs, possession costs and usage costs will apply to all.

6.3 Investment Calculations

From the data presented in the Chapters 4 and 5 and the arguments from the sub-chapter 6.2, the Tables in Appendix B were created. The knowledge about the each customer type was used when evaluating the values, so, by some parts, they differ from the values from Chapter 5. These Tables present the cash flow analysis for online DGA monitoring where the achieved savings are seen as net incomes which are scheduled to the end of the year.

It could be stated that the reduced maintenance costs and reduced failure-related repair or replacement costs apply to all customers and, therefore, should be taken into account in all possible customer cases. The improved loading capacity is mainly the case with GSU power transformers, where the loading rate in normal use is usually 95 %. The lifetime extension is not taken into account at all while doing the calculations, because it cannot be known how the customer would actually use the spared capital. However, it can be considered as a possibility with GSU customers.

6.3.1 Internal Rate of Return

The IRR is calculated with Microsoft Excel from the equation 26. First, the IRR is calculated for each variable and then, the whole net income is taken into account. Compared to NPV, the IRR is expressed in percentage terms which is often easier to understand for people also with non-financial background.

GSU

For the GSU units, the individual IRR for improved loading capacity, reduced maintenance costs, reduced failure-related repair or replacement costs and cost of not-generated power were calculated. The results were 72.6 %, -16.5 %, 29.8 % and 43.5 %, respectively. The total IRR for GSU power transformer was 148.3 %.

It can be argued, whether the improved overloading capacity should be included to the calculation or not, because of its controversial nature as discussed in the sub-chapters 6.3 and 7.1. Without it taken into account, the total IRR for GSU units is 75.7 %.

TSO

For the TSO units, the individual IRR for reduced maintenance costs, reduced failure-related repair or replacement costs and cost of not-delivered energy with N-1 criterion were calculated. The results were -7.5 % and 29.8 %, respectively, while the not-delivered energy does not give the savings at all. The total IRR for TSO power transformer was 33.6 %.

DSO

For the DSO units, the individual IRR for reduced maintenance costs, reduced failure-related repair or replacement costs and cost of not-delivered energy with N-0 criterion were calculated. The results were -7.5 %, -1.5 % and -11.2 %, respectively. The total IRR for DSO power transformer was 8.7 %.

Industry

For the industrial power transformers, the individual IRR for reduced maintenance costs, reduced failure-related repair or replacement costs and cost of lost production were calculated. The results were -16.5 %, -1.5 % and 56.6 %, respectively. The total IRR for TSO power transformers was 64.3 %.

6.3.2 Payback Period

The payback period is calculated with the equation 28 for each customer type.

For the GSU units, the period is 0.7 years and without the lifetime extension the time increases to 1.3 years. For the DSO units the payback period is 8.1 years, for the TSO units 2.9 years and for the industrial units the payback period is 1.6 years.

7. RESULTS AND DISCUSSION

This Chapter presents the results and discusses their meaning in different practices. They give general view about the value creation with each of the customer types: GSU, TSO, DSO and industrial. Also the review of the thesis and proposals for the future actions are given.

7.1 Results

As mentioned before, the exact analysis to general situation cannot be done because of the differences with all the customers. Instead, each of the value creation variables can be recognized and the most significant ones identified.

GSU

The total IRR for GSU power transformers can be considered as high. Together all three income sources form great value for the investment in online DGA monitoring. From the value propositions, the savings gained from not generated power is the greatest one. Reduced failure-related repair or replacement costs are also quite high while, at the same time, the savings from automated oil sampling and reduced maintenance costs is negligible. The payback period of 1.3 years is short.

TSO

The total IRR for TSO power transformers can be considered as high. The savings from not delivered energy in N-1 situation can be considered to be zero. This leaves the benefits to reduced maintenance and failure-related repair or replacement costs, which the latter one is the priority. All in all, the payback period of just less than 3 years can be seen as intermediate level.

DSO

The total IRR for a DSO power transformers can be considered as low. Together all three income sourced cannot create the value for the investment to be highly profitable. The main savings are gained from the reduced failure-related repair or replacement costs. Also reduced maintenance costs and not delivered power are bringing some net incomes, but they do not cover the high price of the DGA unit so soon. This leaves the payback period to over 8 years, which can be considered as long.

Industrial

The total IRR for industrial power transformers can be considered as high. Together all three income sources form great value for the investment in online DGA monitoring. From the value propositions, the savings gained from lost production is the greatest one. Reduced failure-related repair or replacement costs are also quite high while, at the same time, the savings from automated oil sampling and reduced maintenance costs is really low. The payback period of 1.6 years is short.

7.2 Conclusions

The power transformer owner has basically two options when thinking about the condition monitoring of its power transformers. It is possible to take manual oil sample from the power transformer or invest in new online DGA monitor. Online monitor makes it possible to get rid of manual sampling and get the results automatically in almost real-time. This sub-chapter concludes the results of this thesis.

Offline DGA vs. Online DGA

The justification for online monitoring of power transformers is driven by the need of the electrical utilities to reduce operating costs and improve the reliability of their power transformers. The evaluation of data acquired by an online monitoring system shows the capability to detect oncoming failures within the power transformer.

Compared to offline DGA monitoring, the online DGA monitoring improves the failure detection by 75 % increasing the total rate from 50 % to 87.5 %. This can be seen as remarkable improvement. In the future, online DGA monitors can be in important role in automated monitoring and taking the smart grids and asset management to the next level.

Customer Value

Customer value thinking and value selling are more and more popular in all fields of technology. The price for the online DGA monitor has to be justified by the cost savings it creates, and not just by its technical details. When considering investment in online DGA monitors, the decision is usually made in upper management of the customer company. Therefore it is important to understand the created value, which makes it easier to discuss with the non-technical personnel who usually grants the budget for new investments.

The most important research question was to find out the differences in value creation for four different power transformer customer types: GSU, TSO, DSO and industrial customers. The value is created in different situation with each of these types.

The direct economic cost savings can be achieved from improved loading capacity, extended lifetime, reduced maintenance costs and reduced failure-related repair or replacement costs. From which the improved loading capacity and extended lifetime can be seen as possible cost saving targets only in certain power transformer cases: with GSU units and with the units which are already in the end of their lifetime. Reduced maintenance and failure-related repair or replacement costs are valid to all power transformers and to all customer types.

The indirect economic cost savings are achieved from preventing the failure and securing the power supply to the grid or plant. GSU, TSO, DSO and industrial users are able to benefit only with one method from three possibilities, one for each customer type: savings from not-generated energy for GSUs, savings from not-delivered energy for TSOs and DSOs and savings from lost production for industrial customers.

Value Creation

The profitability was evaluated by calculating the IRR and payback period for each individual cost saving type and for the each customer type. The results are presented in the Table 7.1. In the Table, the following evaluation method was used: IRR is considered to be *POOR* when it is negative, the question mark (*?*) was used when the IRR is less than 10 % while *GOOD* signals the IRR more than 10 %. The hyphen (-) means that the particular variable is not valid for this customer type.

The payback period is considered to be *GOOD* when it is less than 4 years. The question mark signals for the payback period less than 10 years while *POOR*, which was not needed in this thesis, is for the payback period between 10 and 15 years, which is close to the lifetime of the online DGA monitor used in the calculations.

Table 7.1 Conclusion.

	Variable IRR	GSU	TSO	DSO	Industrial
Direct Savings	Improved Overloading	GOOD	-	-	-
	Extended Lifetime	ARGUABLE	-	-	-
	Reduced Maintenance Costs	POOR	POOR	POOR	POOR
	Reduced Failure-Related Repair or Replacement Costs	GOOD	GOOD	POOR	POOR
Indirect Savings	Cost of Power Not Generated	GOOD	-	-	-
	Cost of Contractual Power Not Delivered (N-1)	-	POOR	-	-
	Cost of Contractual Power Not Delivered (N-0)	-	-	POOR	-
	Cost of Lost Production	-	-	-	GOOD
	Total IRR	GOOD	GOOD	?	GOOD
	Payback Period	GOOD	GOOD	?	GOOD
	TOTAL	GOOD	GOOD	?	GOOD

The Table 7.1 shows that the biggest value for online DGA monitor is in the indirect savings. When thinking about the sales arguments and the customer value, they vary a lot between the customer types. Reduced maintenance cost can be seen as the only cost saving type which is certain and concrete to all the customers. However, although the savings are undeniable, they are not enough to convince a single customer because of the relatively high price of the online DGA monitor.

The reduced failure-related repair or replacement costs are the biggest driver for TSO power transformer owners, which is due to the high price of the new power transformer. It is also major source of savings to GSU units for the same reason, when DSOs and industrial customers cannot get lot of value from that because of the lower price of their relatively small power transformers.

The biggest customer value lies on the GSU and industrial power transformers, which is because of the high indirect costs in case of the power transformer failure. Also the possibility of improved loading with the GSU units increases the created value. For TSOs and DSOs, the value from indirect savings is not that significant. This is because of the N-1 criterion for TSO power transformers, which makes the probability of the outage extremely low. For the DSOs, the small nominal power and low loading rate decreases the gained benefits and the customer value.

The role of insurance companies was also studied in this thesis. However, despite the fact that they cover costs when a power transformer failure happens, the deductibles may be hundreds of thousands of euros or several months. So, it is not reasonable to use the 12 months business interruption as a sales argument, because of the business interruption insurance with 1 month deductible covers the most of it, but, instead, use the 1 month interruption. Also, it is important to realize that no matter if there are insurances or not, there will always be costs in the case of a power transformer failure.

If a power transformer in question is a suspect of a high potential failure, the investment could be nearly always justified because every time the power transformer fails suddenly, the indirect costs are, in practice, higher than the price of the online DGA monitor. Even the small power transformer can cause serious damages and costs, if there is, for example, a town or a city which suffers the consequences of a failure.

7.3 Evaluation of the Thesis

The research objectives were defined in the sub-chapter 2.3. All the questions were answered in the thesis, and, therefore, the goal of the thesis is fulfilled. The most important goal for this thesis was to understand the customer types and the situations when investing in the online DGA monitoring is a profitable decision. The sub-chapter 7.2 and the Table 7.1 gives a summarized and comprehensive answer to that.

A total of 16 experts from 15 different stakeholders and 6 countries were interviewed to give information about the topic. The interview results were quite similar with all the stakeholders, which proves that the thesis is done with the correct information and right kind of assumptions. It can be said that the interviews were highly important and gave great guidance and set the correct level for gained costs and benefits.

The actual calculation results, IRR and payback period, are calculated correctly. However, the values for these are only directive approximates and they should not be considered as exact accurate.

Earlier published studies, reports and standards have given a good basic knowledge about the topic. They process the value creation by simple examples and do not give any monetary values for them. Therefore it has been unclear which ones are the main targets for value selling. This thesis collects the data from earlier publications and gathers more information from industry experts. Therefore the results of this thesis can be used not only by the product development to understand the online DGA in a wider context, but also by the sales personnel and the strategic management.

7.4 Proposals for Action

Vaisala has good and strong reputation as the measurement device manufacturer all over the world. Still it is important to understand the value the online DGA monitor is providing, highlight the most important features and communicate the customer value as well as possible.

What it comes to value selling, the sales organization should highlight the indirect cost savings as a major sales argument. Other things that can be communicated with the customers, are the functional and psychological benefits which the online DGA is providing, such as the public image of the company and the peace of mind what it comes to evaluating the condition of a power transformer fleet.

At the moment the insurance companies do not require online DGA monitors at all. It would be good for Vaisala's business to start contacting these companies and communicate the benefits the online DGA monitor is providing. If the insurance companies put the online DGA into their insurance requirements, the demand for online DGA monitors would increase a lot.

The main goal of all the business should be making the customers' life easier. At the moment, some customers do not understand how to interpret the DGA measurement results and, despite the DGA monitoring, are facing avoidable power transformer failures. Vaisala could create a guidebook which gives information and instruction about the actions that should be taken when the online DGA monitor gives an alarm.

Lots of calculations were done while doing this thesis. The used Microsoft Excel file could be improved and used as a value tool by the sales organization. This would make it easier to serve each customer individually and find out the customer value precisely in customer's situation. It would be beneficial to interview the customers and calculate the customer value individually with the numbers they give, since the failure probability and other variables may vary significantly due to age and condition of a power transformer fleet.

Many customers do not have their own blue-collar workers at all, but they have outsourced everything related to manual labor. This the case especially with TSOs and bigger DSOs. From customer perspective, it would be easier to invest in Vaisala's devices, if they could buy an assembly and maintenance service from them as well. Therefore it could be beneficial to search for partners from the main market areas and start partnerships with them what it comes to these services.

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APPENDIX A: QUESTIONS FOR INTERVIEWS

Semi-structured interview themes and questions. If the question is irrelevant to you, it can be ignored. Please try to be clear with the differences between TSO, DSO, generation (GSU) and industrial power transformers.

General information

- Name, title, company, e-mail
- Your relationship with power transformer industry
- What kind of (and how many) power transformers your company has at the moment
- How is the loading rate of your power transformers

Failures

- Has there been any power transformer failures
  - When was the last time?
  - How often in general?
- When a power transformer failure happens, what are the total expenses?
  - Direct costs
  - Indirect costs
- What kind of safety or backup systems you have for a power transformer failure?
- Is there different kind of prioritization for different power transformers?
- Who repairs/renews the failed power transformers?
  - Where is it done?
  - How long it takes?
  - Direct and indirect costs?

Offline condition monitoring

- How is the power transformer condition monitoring handled at the moment?
  - Do you have any plans to change the methods in the near future?
- How often do you take offline oil samples from your power transformers?
  - How much it costs to take a sample and analyze it in a laboratory?
  - Who takes the samples and does the analyzing?
- What are the most important gases for you to measure?
- Have you successfully prevented a power transformer failure because of the offline oil analyzing?
  - How often this happens?

Online condition monitoring

- Have you installed any kind of power transformer online monitors for oil analysis?
    - What kind of devices you have?
- Have these devices prevented any power transformer failures?
- Is it possible to replace the offline oil sampling with online monitoring completely?

Online monitor as an investment

- What are the total expenses when investing in online monitor?
    - Device itself, installing, data connections, maintaining, training
- Who makes the actual installation?
    - Outsourced?
- How is the decision making process done?
- What kind of financial calculations are made?
- How do you count the actual costs and benefits?
- Who makes the actual decision?
- Do you buy your power transformer via tender?

Insurances

- What can be insured?
- What can be covered by insurance?
- How big is the customer's responsibility when failures happen?
    - Direct and indirect costs
- Does the insurance companies have any kind of incentives that encourages companies to do the oil gas analysis?
- Differences between the insurance companies?

Other

- Other comments?

APPENDIX B: CASH FLOW ANALYSIS TABLES

Table B.1 Cash Flow Analysis for Online DGA Monitor in GSU Power Transformer.

Year	B_o	B_M	B_F	C_{nq}	Net Income	C_A	C_U	Cash Flow
0						-40,000 €	-4,000 €	-44,000 €
1		700 €	13,371 €	19,237 €	33,308 €			33,308 €
2		700 €	13,371 €	19,237 €	33,308 €			33,308 €
3		700 €	13,371 €	19,237 €	33,308 €			33,308 €
4		700 €	13,371 €	19,237 €	33,308 €			33,308 €
5		700 €	13,371 €	19,237 €	33,308 €			33,308 €
6		700 €	13,371 €	19,237 €	33,308 €			33,308 €
7		700 €	13,371 €	19,237 €	33,308 €			33,308 €
8		700 €	13,371 €	19,237 €	33,308 €			33,308 €
9		700 €	13,371 €	19,237 €	33,308 €			33,308 €
10		700 €	13,371 €	19,237 €	33,308 €			33,308 €
11		700 €	13,371 €	19,237 €	33,308 €			33,308 €
12		700 €	13,371 €	19,237 €	33,308 €			33,308 €
13		700 €	13,371 €	19,237 €	33,308 €			33,308 €
14		700 €	13,371 €	19,237 €	33,308 €			33,308 €
15		700 €	13,371 €	19,237 €	33,308 €		-1,000 €	32,308 €

Table B.2 Cash Flow Analysis for Online DGA Monitor in TSO Power Transformer.

Year	B_M	B_F	$C_{nd(N-1)}$	Net Income	C_A	C_U	Cash Flow
0					-40,000 €	-4,000 €	-44,000 €
1	1,600 €	13,371 €	0 €	14,971 €			14,971 €
2	1,600 €	13,371 €	0 €	14,971 €			14,971 €
3	1,600 €	13,371 €	0 €	14,971 €			14,971 €
4	1,600 €	13,371 €	0 €	14,971 €			14,971 €
5	1,600 €	13,371 €	0 €	14,971 €			14,971 €
6	1,600 €	13,371 €	0 €	14,971 €			14,971 €
7	1,600 €	13,371 €	0 €	14,971 €			14,971 €
8	1,600 €	13,371 €	0 €	14,971 €			14,971 €
9	1,600 €	13,371 €	0 €	14,971 €			14,971 €
10	1,600 €	13,371 €	0 €	14,971 €			14,971 €
11	1,600 €	13,371 €	0 €	14,971 €			14,971 €
12	1,600 €	13,371 €	0 €	14,971 €			14,971 €
13	1,600 €	13,371 €	0 €	14,971 €			14,971 €
14	1,600 €	13,371 €	0 €	14,971 €			14,971 €
15	1,600 €	13,371 €	0 €	14,971 €		-1,000 €	13,971 €

Table B.3 Cash Flow Analysis for Online DGA Monitor in DSO Power Transformer.

Year	B_M	B_F	$C_{nd(N-0)}$	Net Income	C_A	C_U	Cash Flow
0					-40,000 €	-4,000 €	-44,000 €
1	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
2	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
3	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
4	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
5	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
6	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
7	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
8	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
9	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
10	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
11	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
12	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
13	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
14	1,600 €	2,674 €	1,130 €	5,404 €			5,404 €
15	1,600 €	2,674 €	1,130 €	5,404 €		-1,000 €	4,404 €

Table B.4 Cash Flow Analysis for Online DGA Monitor in Industrial Power Transformer.

Year	B_M	B_F	C_{tlp}	Net Income	C_A	C_U	Cash Flow
0					-40,000 €	-4,000 €	-44,000 €
1	700 €	2,674 €	24,937 €	28,311 €			28,311 €
2	700 €	2,674 €	24,937 €	28,311 €			28,311 €
3	700 €	2,674 €	24,937 €	28,311 €			28,311 €
4	700 €	2,674 €	24,937 €	28,311 €			28,311 €
5	700 €	2,674 €	24,937 €	28,311 €			28,311 €
6	700 €	2,674 €	24,937 €	28,311 €			28,311 €
7	700 €	2,674 €	24,937 €	28,311 €			28,311 €
8	700 €	2,674 €	24,937 €	28,311 €			28,311 €
9	700 €	2,674 €	24,937 €	28,311 €			28,311 €
10	700 €	2,674 €	24,937 €	28,311 €			28,311 €
11	700 €	2,674 €	24,937 €	28,311 €			28,311 €
12	700 €	2,674 €	24,937 €	28,311 €			28,311 €
13	700 €	2,674 €	24,937 €	28,311 €			28,311 €
14	700 €	2,674 €	24,937 €	28,311 €			28,311 €
15	700 €	2,674 €	24,937 €	28,311 €		-1,000 €	27,311 €